Stochastic fault tree analysis for agropark project appraisal

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Abstract

Agroparks offer in theory a variety of economic advantages and environmental benefits. Since agropark projects are typically capital intensive and with high societal impact, appraisal from lenders and policy makers will play a key role in the realisation of the concept. In practice, however, project appraisal is hampered by the complexity of the concept and the multitude of risks. In this paper, a methodology based on stochastic fault-tree analysis (FTA) was developed to support project managers and policy makers in making agropark investment decisions. The methodology is illustrated with an example agropark project.

Keywords

Fault tree analysis (FTA), agroparks, formation risk, Monte-Carlo simulation

Executive Summary

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Agroparks offer in theory a variety of economic advantages and environmental benefits. To implement the concept, project appraisal is a crucial step which determines the success of the project. Since agropark projects are typically capital intensive and can have large societal impacts, appraisal from lenders and policy makers will play a key role in the realisation of this concept. In practice, however, project appraisal is hampered by the complexity of the concept and the multitude of risks. In this paper, a methodology based on stochastic fault-tree analysis (FTA) was developed to support project managers and policy makers in making agropark investment decisions. FTA takes into account the logical functional relationships among agropark subsystems and among key components of each subsystem. In the case of agropark project, the formation risk is jointly determined by the possibility of obtaining financing and legal permits and the chance of establishing collaboration among different firms, which in return depend on a large number of factors. FTA uses deductive reasoning to systematically identify and assess the formation risk.

As an illustration, a FTA model is built for an agropark project comprising a poultry unit, a pig unit and a central processing unit which uses anaerobic digestion of livestock waste to produce renewable energy. Formation risk of the agropark project is assessed by assessing the possible failure in obtaining financing, legal permits and in establishing the collaboration among the firms according to the agropark concept. These possible failure factors were then further decomposed into business risks, credit conditions, and trust among the participating entrepreneurs. To assess the uncertainty of the formation risk, Monte-Carlo simulation was carried out to provide quantitative insight into the variability of the outcomes. The root causes of undesired failures in the agropark system were identified by means of reliability tests.

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Introduction

An agropark is envisaged as a spatial cluster of agricultural-related functions, which aims to apply the principles of industrial ecology in the agrosector (Smeets, 2011). In general, the theoretical foundation of agroparks is that through spatial clustering and fine-tuning of different activities synergetic effects can be created, such as efficient land use due to concentration of firms, efficient logistics due to reduced transportation, and collective learning due to interaction among entrepreneurs. Moreover, through intelligent design and controlled production systems, random effects of nature and waste of resources will be minimized (De Wilt and Dobbelaar, 2005; Breure et al., 2007). An ideal agropark is therefore a planned agribusiness system in which all activities are geared towards sustainable development, and additional economic benefits are created due to more efficient use of resources.

The development of agroparks entails new business models to capitalize on the opportunities created by spatial clustering and cooperation. To implement the agropark concept, project appraisal will be crucial. Since such projects are typically capital intensive and have potentially large social and environmental impact, appraisal from lenders and policy makers will pay a key role in the realisation of agroparks. The appraisal from policy makers is important for two reasons. First, the value proposition of the agropark business model often includes the generation of nonmarket goods such as the reduction of CO2 for which policy support is often necessary. Second, the design and performance of an agropark must meet requirements set by policy makers to ensure social welfare. Due to the novel nature of business model for agroparks, it often difficult for policy makers to evaluate the performance of an agropark. In general, agropark project appraisal is hampered by the complexity of the concept and the multitude of uncertainties which would have an bearing on the viability and profitability of agroparks (van Someren and Nijhof, 2010).

As a system innovation, the concept of agropark encompasses technological, market and institutional uncertainties which can lead to significant risks to the stakeholders involved. Technical and economic interdependencies among different stakeholders implied by the integration of different business activities add an extra level of complexity to the risk analysis of agroparks. To support managers in making agropark investment decisions, a methodology must be developed which takes into account these characteristic features of agroparks.

The purpose of this paper is to introduce a methodology based on stochastic fault-tree analysis (FTA) for agropark project appraisal. From a system design perspective, the FTA framework provides a logical framework for understanding the way in which an agropark project can fail, which is essential for agropark project appraisal. The methodology is illustrated with an agropark project comprising a pig unit, a poultry unit, and a central processing unit which produces bioenergy through anaerobic digestion of manure.

The paper proceeds as follows. The next section provides a brief introduction to stochastic fault tree analysis and describes the model specification for the example agropark. The results are then presented and discussed in the section that follows. After that, the paper concludes with a brief outlook on extensions of the model and future research.

Stochastic FTA for an agropark project

Basic principles of FTA

FTA was originally developed in the early 1960's by Watson and Mearns of Bell Laboratories for the safety analysis of launch control systems (Watson, 1961). Application of FTA increases the understanding of the safety and reliability issues whilst highlighting the potential improvements that may be achieved through alternative designs (Khodabandehloo, 1996; Ferdous et al., 2011). Although FTA is commonly applied to industrial systems to study possibilities of technical failure, fault tree theory can also be of use for economic risk assessments (Gatfaoui, 2008).

FTA is a deductive and probabilistic risk assessment tool which elucidates the causal relations leading to a given undesired event (termed top-event). The terms "Failure" and "Fault" have specific meanings in the context of risk management with "Failure" referring to the non-functioning of a specific item of equipment and "Fault" referring to the non-function of a system or sub-system. A fault tree is typically developed top-down by decomposing the top-event (a fault) into its possible causes (failures). Each possible cause is then investigated and further refined until the primary events are identified. The primary events (also called base-event) constitute the limit of resolution of the FTA (Sutton, 2007).

The resolution of the top-event into its constituent causes and further down to the base-events is generally implemented by logical AND-OR gates among events. An OR gate () is a logic gate that gives a positive output if one or more of the input events to the gate are positive (i.e., a failure occurs). The mathematics of an OR gate is described in Equation (1):

$$\lambda_G = 1 - \prod_{i=1}^{n}(1-\lambda_i), \quad (1)$$

where λ_G represents the value of output event through the OR gate given a total of n input events to the gate, and λ_i denotes the value of the i^{th} input event. The value of λ refers to the likelihood of the input event or output event happening, which can be expressed as failure rates or probabilities .

The second type of logical gate mostly used in fault trees is the AND gate (), whereby all the inputs to an AND gate must be positive for the output to be positive. The output value of an AND gate is the product of the values of the input events as described in Equation (2). This type of gate represents an increased reliability and safety since the overall likelihood of fault is always lower than likelihood of the input events.

$$\lambda_G = \prod_{i=1}^{n} \lambda_i \quad (2)$$

Although other types of gate (e.g., the VOTE gate) are sometimes used, they can all be created from a combination of OR and AND gates (Sutton, 2007).

Stochastic FTA for an agropark

Conventional FTA usually assumes exact probabilities of the events. These deterministic probabilities are collected from historical observations or derived from experiments. Observational probabilities are appropriate for physical processes, but may be hard to assess for decision problems that are non-repetitive, one-time events, or are subjective by nature (for example trust). This may be a reason for the popularity of subjective probability in decision models (Munera, 1992). Moreover, randomness in the outcome of events is not accounted for. To address these issues that are prevalent in agropark projects, we propose a stochastic FTA in which subjective information is used in combination with Monte Carlo simulation (MC) to obtain the joint distribution from the basic (subjective) probability distributions and to assess the uncertainty in the estimated probabilities. MC simulation is considered an appropriate and very flexible method of investigating aspects that are stochastic in nature (Vose, 2000). Risks are incorporated by random sampling from a priori specified probability distribution for variables affecting the events in the fault tree model. Many random numbers are drawn to reflect the likelihood of different outcomes of each probability distribution. For our illustration, the stochastic FTA was modelled and analysed with @Risk (Palisade, 2009).

Although in theory various agropark configurations are promising, intensive livestock production is often considered an important element within an agropark (see e.g. cases in Smeets, 2011). Intensive livestock production requires large amounts of input (i.e., feed and energy) and produces large amounts of waste materials and by-products (i.e., manure). Spatial clustering of livestock units with other agricultural activities will facilitate exchanges of material and energy flows. For example, by investing in a central processing unit (CPU), manure from different farms can be used to produce bioenergy through anaerobic digestion (AD). Spatial clustering in this way saves transportation costs and energy, and reduces the environmental impact of intensive animal farming. The configuration of such an agropark (AP) is shown in Figure 1, which consists of a pig farm (farm A), a poultry unit (firm B), and an central processing unit (firm C). The example is based on the New Mixed Farm (NMF) currently being implemented in the Netherlands (see e.g., van Someren and Nijhof, 2010). To simplify the illustration, only key interactions and products are presented. In agropark AP, Firm C uses the manure from A and B to produce renewable energy through anaerobic digestion. Alternatively, as shown by the dotted lines, manure can be collected or disposed of in the market where the price fluctuates greatly. Without the agropark, Firm C could receive payment for collecting the manure from the market. On the contrary, firm A and B may need to pay for manure disposal. Cost of manure disposal is influenced by a number of factors such as the demand for manure by arable farms and the distance from the animal farms to the destination.

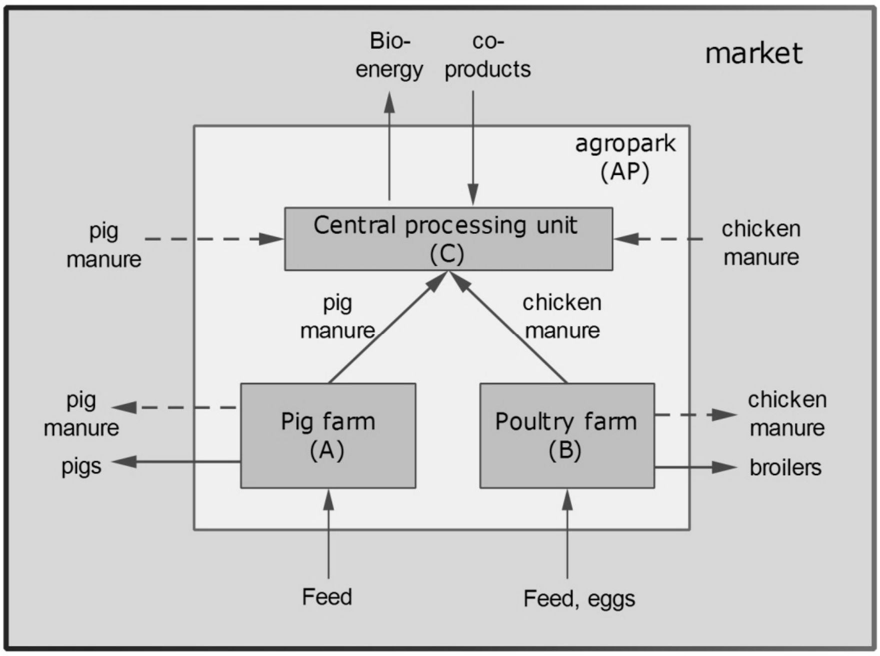

Figure 1. Configuration of an agropark comprising three firms

Local processing of excessive manure reduces transport costs for manure and its environmental impact (e.g., stench and soil pollution) of the animal farms, which creates both economic and environmental benefits. To capitalize on such benefits novel business models must be designed to ensure technological and organizational cooperation among the firms. The interdependency implied by such business models has presented difficulty for regulators or investors to evaluate the agropark project as investment risk of one firm is now influenced by investment risks of other firms. In addition to business risks of the individual firms, it becomes crucial to assess the viability of the whole concept, i.e., the formation risk of agroparks. As such, the AP construction comprising three firms entails distinctive business risks from a large firm with three different activities.

For agropark AP, a fault tree model can be developed with the top-event captures the formation failure of an envisaged agropark. Following the agropark concept, three undesirable events can lead to the failure of the agropark concept through an OR gate: no legal permit (E1), no financing (E2), and no collaboration (E3). These events can be further decomposed to identify the base events. Further decomposition of the causes requires however more detailed information about the business model and the operations. For example, whether legal permits and loans are to be obtained for all three firms together or separately. For illustrative purpose, we assume that the permits and loans are applied separately. This leads to an OR gate for the event E1 and E2 since permits and financing are needed for all three firms in order to realize the technical cooperation.

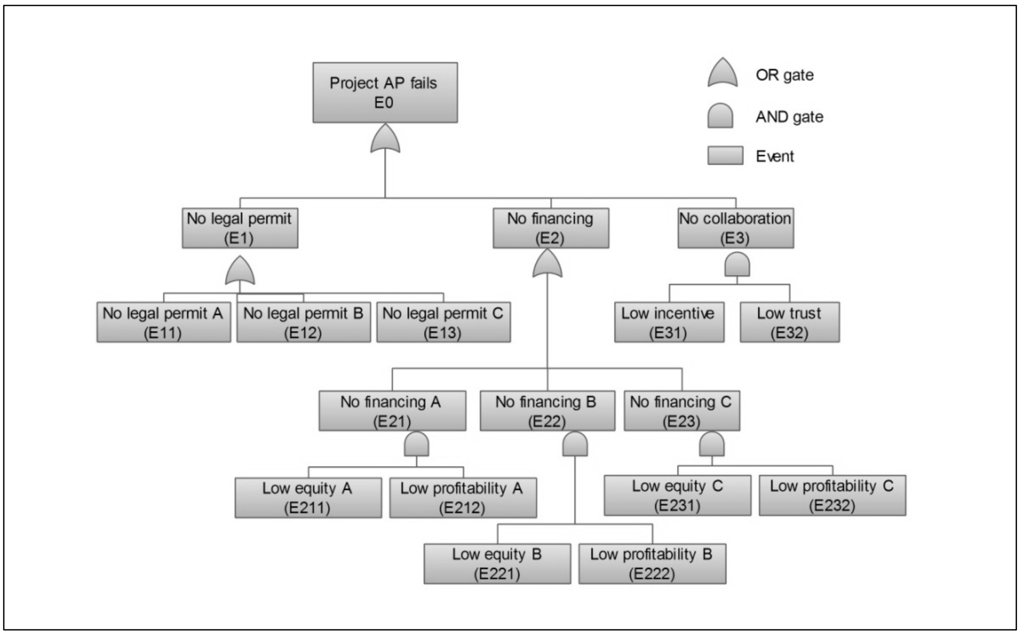

Figure 2. Fault-tree logic diagram of the agropark under study.

Unlike the OR gates for the events E1 and E2, an AND gate is considered for event E3. This is based on the reasoning that high level of trust among the entrepreneurs can prevent opportunistic behaviour induced by economic incentives. On the other hand, when trust relationship is not yet established, high economic incentive can induce the entrepreneurs to commit to the collaboration as well.

Data and parameters

To assess the failure rates for the events in the FTA model, investment information of the firms was based on the planned NMF agropark, with modifications for confidentiality reasons. To evaluate the relative performance of the firms and assesses their business risk profiles, statistical data about the pig production, poultry production and AD systems were retrieved from the Farm Accountancy Data Network (FADN) collected by LEI, Wageningen UR and two accountancy firms in the Netherlands (e.g., AgroVision and Alfa Accountants).

The firms A, B and C are still in a process of obtaining legal permits and the outcome remains uncertain. Failure rates for the events “no legal permit” were therefore elicited from a group of experts who are familiar with the firms and the developments in policy making with regard to the firms. The livestock industry in the Netherlands is subject to a growing number of laws and regulations concerning its environmental impact, animal welfare, and public health impact. Obtaining all required permits can be a laborious and lengthy process. Assessing the failure rates requires therefore good knowledge of the sector and its social and institutional environment.

Table 1. Probability distributions of stochastic variables used in the simulation model

Category and firm	Unit	Distribution	Parameters
Technical			
Pig farm			
Pig production	Kg	Pert	(min, m.l., max)*
Feed conversion ratio	dimensionless	Pert	idem
Manure production	Kg	Pert	idem
Poultry farm			
Chicken production	Kg	Pert	idem
Feed conversion	Dimensionless	Pert	idem
Manure production	Kg	Pert	idem
CPU			
Biogas production per kg manure	M^3/kg	Pert	idem
Marketing			
Pig farm			
Price of piglets	€/piglet	Lognormal	(mean, std)
Pork price	€/kg	Lognormal	idem
Feed price	€/ton	Lognormal	idem
Transport costs	€/km	Pert	(min, m.l., max)
Poultry farm			
Price of hatching eggs	€/100eggs	Lognormal	(mean, std)
Price of chicken feed	€/ton	Lognormal	(idem
Transport costs	€/km	Pert	(min, m.l., max)
CPU			
Manure price	€/ton	Pert	idem
Co-product price	€/ton	Lognormal	(mean, std)
Transport costs	€/kwh	Pert	(min, m.l., max)
Electricity price	€/kwh	Lognormal	(mean, std)
Subsidy on renewable energy	€/ton	Binomial	(n, p)

* where min = minimum, m.l.=most likely, max =maximum;

The failure possibility of obtaining financing and establishing collaboration would depend on the business model of the whole agropark concept. The business model should specify the governance structure and coordination mechanism among the firms with regard to the cooperation. Different institutional arrangements can lead to different incentive structures and result in different formation risks. As an example, we assume contractual arrangements in which C should only process manure from A and B. At the same time, manure from A and B should be exclusively delivered to C. It is also assumed that firms determine the manure price based on market price corrected for the transport costs to a common reference location. This exclusivity, while ensuring the reduction of transportation costs, restricts the possibility to make use of favourable market condition. For example, when market payment for collecting manure increases, cooperation within the park would put C at an economic disadvantage. This can be seen as a disincentive to cooperate in the agropark.

To assess the profitability of the firms, stochastic capital budgeting models are built for the three farms in @Risk, where probability distributions are specified for the key technical and economic variables. For a number of key performance indicators, the distributions and their parameters are shown in Table 1. Failure rates of the events E212 (low profitability of firm A), E222 (low profitability of firm B), E232 (low profitability of firm C), E31 (low incentive to cooperate) and E32 (low trust) were obtained through MC simulation and counting the occurrence of the underlying event not meeting the minimum requirements. The minimum requirements are also elicited from experts with relevant expertise, which can be used as a default value. Since the minimum requirement of the decision maker can differ from these default values, the failure rates should be interpreted in the probabilistic sense.

The outputs of the MC simulation models are presented in Table 2, which can be seen as the risk profile of the involved firms. For investors and governmental authorities, insights into the risk profiles are important to decide whether or not to grant financial or legal approval. The incentives are simulated as the percentage of the potential gain from the cooperation in terms of reduced transport costs to the total investment, which depends on the amount of manure and a reference distance. The simulation outputs show different levels of variability in the profitability of the firms. The variability results from many random factors in the production process and the market. During the MC simulation, a correlation matrix is defined between a number of variables as they tend to move simultaneously. For example, when feed prices increase, the prices for pigs and poultry usually also increase. This is modelled by a positive correlation among the price variables. The correlation coefficient is estimated using the price information of the Dutch market.

To assess the failure probability of obtaining financing and establishing collaboration, the criteria used to grant financing or accept cooperation should be made clear. In other words, the failure is modelled as the probability that the agropark fails to meet the criteria. These criteria are the subjective inputs which can vary across the decision-maker, be it a natural person or an institution. To assess the probability of these 'man-made' risks, the criteria used by the decision-makers must be first assessed or elicited. The criteria used for the example model are shown as the following table (Table 3).

Table 2. Risk profiles of the agropark firms

	Firm A	Firm B	Firm C
Revenue (mln€)			
Mean	12.5	23.5	15.0
Standard deviation	6.5	10.5	9.0
Variable input costs (mln€)			
Mean	5.5	11.5	8.0
Standard deviation	3.0	5.5	2.0
Fixed input costs (mln €)			
Mean	5.5	10.0	5.0
Standard deviation	0.0	0.0	0.0
Incentives (%)			
Mean	6.5	6.0	10.0
Standard deviation	0.5	0.5	5.5

Table 3. Criteria used by relevant decision-maker for agropark appraisal

	Firm A	Firm B	Firm C
Profitability (%)			
Minimum requirement of the government	10	10	10
Solvency (%)			
Minimum requirement of the bank	30	30	30
Incentives(%)			
Minimum requirement of the entrepreneur	10	10	10

Results and discussion

Failure rates of the causal events

Using the data and methods described in previous section, the failures probabilities for the main events are first presented in Table 4. While the estimated failure rates for the cooperation among the entrepreneurs are low, it is much more likely that the agropark cannot obtain legal permits (46%) and financing (34%). It should be noted that the failure rates cannot be generalized to other agroparks as the criteria used for other agroparks may significantly differ from those in the example agropark. However, it will be a common feature for agroparks that the failure rate of agropark formation will be higher than the failure rates of individual firms. This results from the fact that an OR gate connects the failures of the individual firms to the system. In other words, while the interconnectedness of the agropark firms can generate economic and environmental benefits, the interdependency among the firms due to the common agropark project can greatly increase the formation risk of such construction. This risk must be taken into account when assessing the feasibility of an agropark project.

Different system components would also significantly influence the failure rates. For AD systems, a sufficient return on investment can only be expected on a larger scale (Gloy and Dressler, 2010). On the other hand, in comparison to other agricultural activities, obtaining legal permits for large-scale intensive livestock production are often difficult (van Someren and Nijhof, 2010).

Table 4. Failure probabilities of the events

	Firm A	Firm B	Firm C
No legal permit			
Maximum	0.65	0.85	0.95
Most likely	0.35	0.45	0.55
Minimum	0.25	0.35	0.35
Low profitability			
Maximum	0.35	0.55	0.70
Most likely	0.25	0.35	0.50
Minimum	0.15	0.15	0.30
Low equity			
Maximum	0.45	0.75	0.80
Most likely	0.35	0.55	0.50
Minimum	0.15	0.35	0.30
Low incentive			
Maximum	0.35	0.35	0.35
Most likely	0.25	0.25	0.25
Minimum	0.15	0.15	0.15
Low trust			
Maximum	0.30	0.30	0.30
Most likely	0.20	0.20	0.20
Minimum	0.10	0.10	0.10

One of the major challenges in quantifying the risk of project failure is that the failure rates of the base events are uncertain for a number of reasons. Firstly, historical data for any items that are inherently reliable are only limited available and fragmented. Then, even when there is a reliable data set, the world has become such a turbulent place that the relevance of such historical observations to modelling the future is dubious. For example, technological improvement will have decreased the fault probability values of certain items over time. Thirdly, adjustments to these sparse data are made in order to make them more relevant to the uncertainty in the future period. This could entail more subjective revisions based on the beliefs about the future of the decision maker or other experts. Moreover, a number of perception nodes quantified are subjective in nature (for example trust between investors in an agropark). Although subjectivity captures the specific discerning interpretations it is also subject for introducing uncertainty. As a result, these criticisms might be so serious that there could be little confidence in the predicted results. However, with regard to risk analysis, high precision is not always required to obtain useable and credible results because of the Pareto Principle. Even if the results of the FTA analysis are less strong, as a result of sparse and subjective data, recommendations will not likely change. Certain items are the major contributors to unreliability, and they are the ones that should be addressed. If a long period is expected for the development of an agropark, possible learning effects must be considered when estimating the probabilities, which can be implemented in combination with a Bayesian belief network (Maglogiannis et al., 2006)

Formation risk of the agropark

The minimum required return on assets should be elicited for the investors to calculate the chance that the incentive offered by the agropark project doesn’t meet their requirement. Moreover, three-point estimates were elicited to parameterize the PERT distribution for the nodes “Permit” and “Trust”. Judgements are needed about lowest, highest and modal or most likely values. This simplicity makes it particular useful in cases when no sample data are available and the distribution is to be assessed wholly subjectively. Like the triangular distribution, the PERT distribution emphasizes the "most likely" value over the minimum and maximum estimates. However, unlike the triangular distribution the PERT distribution constructs a smooth curve which places progressively more emphasis on values around (near) the most likely value, in favour of values around the edges. In practice, this implies that we estimate “Permit” and “Trust” for the most likely value, and we believe that even if it is not exactly accurate (as estimates seldom are), we have an expectation that the resulting value will be close to that estimate.

Dynamic analysis of the FTA

To account for the randomness of the basic probabilities the aggregated top-event results were based on 10.000 replications using Monte-Carlo methods. By means of Bayesian updating, the impact of new information on the probabilities in the stochastic fault tree is assessed. Bayesian updating has attracted much attention as a possible solution for the problems of decision support under uncertainty.

Table 5. Updating formation risk of the agropark

	Minimum	Most likely	Maximum
Default	0.40	0.65	0.95
With legal permits	0.25	0.35	0.50
Unconditional cooperation	0.20	0.35	0.70
Increased profitability	0.15	0.35	0.60

The reliance on just a few observations of recent historical records entails a considerable risk of generating misleading results, perhaps seriously so. It is therefore wise to make some adjustments to these sparse data in order to make them more relevant to the uncertainty in the future period. This could entail more subjective revisions based on the beliefs about the future by the decision maker or experts. Moreover, a number of perception nodes are subjective in nature (for example trust between investors in an agropark). Because of insufficient data and inherent subjective aspects to parameterise the FTA model subjective expert knowledge was elicited to complement the recent technical en economic observations. Adding subjective information will retain and re-use knowledge of the actors to make effective use of their knowledge and experience of previously completed projects.

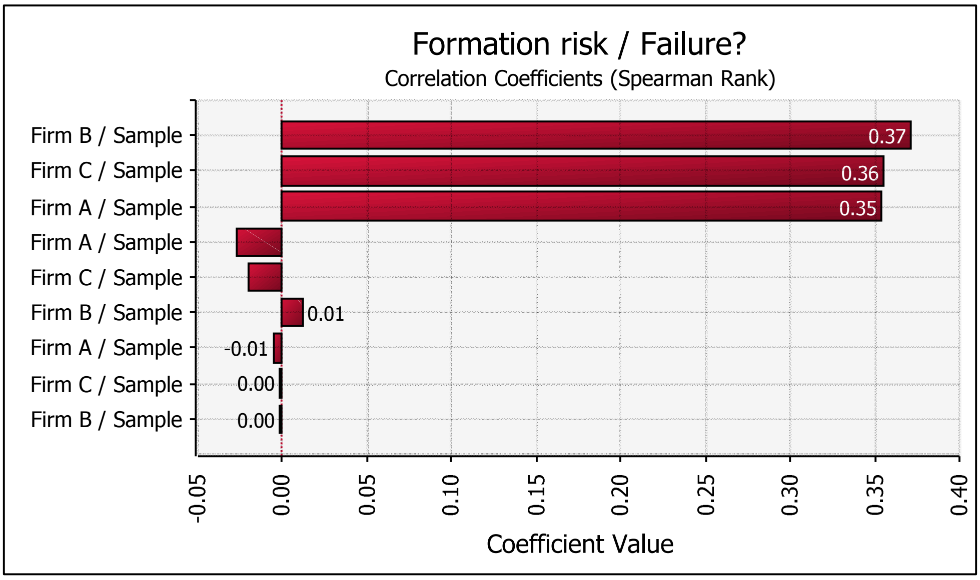

Figure 3. Sensitivity analysis of the causal events for the agropark under study

As explained earlier in this paper, the level of formation risk determines critically on the composition of the agropark and the characteristics of the entrepreneurs. These features are modelled with the parameters determining the probability distributions of the variables. To identify the main causes of the system failure, sensitivity analysis was performed on a number of parameters simultaneously (subjective criteria, likelihood to obtain legal permit). Based on the outcome, it can be observed that the root causes for formation failure are the criteria set on profitability and incentives. This implies that it is important for key stakeholders to communicate on the criteria used in order to increase the chance of successful formation.

Conclusion and further research

In this paper, a stochastic FTA was introduced as a methodology for agropark project appraisal. The methodology combines deductive reasoning and stochastic simulation to assess the formation risk of agroparks. For agropark projects, the FTA can be used to identify key success conditions for formation through systematic analysis of events that negatively influence the crucial aspects: financing, legal permits and collaboration. In particular, formation risk of an agropark is assessed using the functional relationships implied by the agropark concept and the interdependency of the participating firms. As illustrated by the example, the FTA provides a logical framework for understanding the way in which the agropark formation can break down and for identifying the root causes of the systemic risk. A stochastic FTA enables inclusion of uncertainties about the failure rates which is typical of agropark projects. It is expected that the methodology will be of great use to decision-makers for agropark project appraisal.

For illustrative purpose, the presented stochastic FTA considered an agropark with only limited functionality in terms of interactions among the firms. The number of firms is kept to a minimum in order to simplify the illustration. To enable the best possible technological combinations of enterprises and organizational match of stakeholders, a more comprehensive agropark might be even more viable. For example the exchange flows of waste materials could be enhanced by adding a greenhouse horticulture unit in order to utilise CO_2. Possible configurations seem unlimited but will result in a more complex fault trees. Future research can make use of computer-aided FTA to assess formation risk and operational risks for agropark project appraisal.

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