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17.7 A System dynamic enhancement for the scenario technique

A. Brose[1], A. Fügenschuh[2], P. Gausemeier[1], I. Vierhaus[3], G. Seliger[1]
[1] Institut für Werkzeugmaschinen und Fabrikbetrieb, Berlin, Germany
[2] Helmut Schmidt University / University of the Federal Armed Forces Hamburg, Germany
[3] Department Optimization, Zuse Institute Berlin, Germany

Abstract:
The Scenario Technique is a strategic planning method that aims to describe and analyze potential developments of a considered system in the future. Its application consists of several steps, from an initial problem analysis over an influence analysis to projections of key factors and a definition of the scenarios to a final interpretation of the results. The technique itself combines qualitative and quantitative methods and is an enhancement of the standard Scenario Technique. We use the numerical values gathered during the influence analysis, and embed them in a System Dynamics framework. This yields a mathematically rigorous way to achieve predictions of the system's future behavior from an initial impulse and the feedback structure of the factors. The outcome of our new method is a further way of projecting the present into the future, which enables the user of the Scenario Technique to obtain a validation of the results achieved by the standard method.

Keywords:
Scenario Technique; System Dynamics

1 INTRODUCTION

The Scenario Technique is a method for systematically studying a system, and to create consistent scenarios of its future. A scenario is consistent, if it does not contain internal contradictions. According to Garcia [1], a system is defined here as "a set of interrelated elements, where any change in any element affects the set as a whole". Scenarios can be useful to broaden one's view for the various states a future system could take. In this respect the Scenario Technique has proven its value in contexts ranging from business applications to world models, c.f. Chermack et al. [2].

System Dynamics is a method to describe a system (in the sense of Garcia [1]) by stocks and flows, and functional relations between those. The dynamic of the system is governed by feedback loops. Due to the non-linear equation structures it is only possible to analyze the future or long-term behavior of such systems for specially structured and small systems. For realistic and large applications of System Dynamics one applies simulation techniques. Here the current state of the system is projected into the future using the mathematical equations that describe the system. System Dynamics was applied as a tool to understand the behavior of complex systems (for example companies or supply chains) and to develop policies to move the system into a desired state, c.f. Sterman [3].

This paper develops an enhancement of the classical Scenario Technique according to Gausemeier et al. [4]. It replaces some of the steps of the scenario process with steps from the field of System Dynamics. We briefly introduce the two futures techniques, Scenario Technique and System Dynamics, in Section 2. We first explain our new method using a simplified mini-world model of Bossel [5] as an introductory example in Section 3. A concluding summary of our results is provided in Section 4.

2 FUTURES TECHNIQUES

Below we give a brief introduction to the two futures approaches, Scenario Technique and System Dynamics.

2.1 Scenario Technique

Scenario Technique has its origins in the early second half of the 20th century. US-researchers coined the term "scenarios" to describe the potential outcomes of a nuclear confrontation between the two post World War II super-powers USA and USSR [6]. Originating as a military planning tool, the concept of scenarios developed into a business planning tool to help create strategies for the future [7]. Shell Oil started using scenarios in the 1970s to anticipate changes in the market. The oil crises of the 1970s further emphasized the need for prognosis methods that could take structural changes into account [8]. In this context the Scenario Technique developed into a useful instrument, whose main use is to create consistent scenarios and thus broaden the horizon of the minds of decision-makers by presenting them alternative futures, and to make them accept

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the fact that the future can be vastly different from the present [9]. It helps in identifying future threats and opportunities, so that strategies can be based upon these results. However, the Scenario Technique has its weaknesses. In particular, the system's feedback structure, which is generated by the elements of the system influencing one another, is not analyzed in great detail. What is more, once the scenarios are generated, there is no further information on how exactly to make use of the opportunities and how changes will affect the system. Precisely these aspects are focal points the System Dynamics method for futures studies, to be presented in the next section.

A scenario is defined as a "descriptive narrative of plausible alternative projections of a specific part of the future" [10]. However, when speaking of *the* Scenario Technique, we have to acknowledge that there is actually a great number of different Scenario Techniques [11]. Martelli [12] calls this the "methodological chaos" prevailing in the field of futures studies. We focus here in particular on the methodology of Gausemeier et al. [4]. Below we outline its individual steps. According to the typology of Borjeson et al. [13], the Scenario Technique applied in this paper creates explorative, external scenarios. "Explorative" means the method aims to create several scenarios of possible events set in a distant point in time, allowing a structural change to happen. "External" means only those drivers which are beyond the control of those planning are taken into account.

2.2 System Dynamics

The development of System Dynamics is generally attributed to the MIT Professor Jay W. Forrester. Forrester developed in the 1950s a method of depicting a given system in a simple way, which enabled simulations of the system to be run by computers and the reasons for undesirable system behavior to be identified [14]. His method describes a system using "stocks" and "flows", whereby a stock is an accumulation of something and a flow represents a movement of this something from one to another stock. A flow is normally understood as a movement of stock per time, for example, 2 liters per hour [15].

Forrester states that knowing a system's internal structure is more important towards understanding its behavior than being aware of the external influences affecting the system [14, 15]. This is contrary to most people's and perhaps especially manager's fondness of blaming external drivers beyond their control for bad results or unwanted system behavior in general [1].

The conversion of a real life system into a simulation model can be achieved using Forrester's six step process [16]. In general, this is an iterative process involving much changing and customizing of the preceding steps. The goal of the process is to understand the system, so that unwanted system behavior can be corrected in an appropriate way.

3 DEVELOPMENT OF A COMBINED METHOD

Scenario Technique and System Dynamics were both developed in the USA, roughly at the same time. Both methods have the goal to find an adequate description of what potentially happens in the (far) future. However, the way of achieving this goal is quite different. A combined method would have the advantage of creating consistent scenarios, while at the same time being able to simulate a model's behavior over time. The simulation aspect allows the user to identify what Forrester calls "high leverage policies". These are elements of the system, which have a strong influence on the system's overall behavior when they are changed. Identifying these elements can prevent the typical mistake of trying to change the system's behavior by attacking only the symptoms of an undesirable behavior [14].

3.1 Setting up the model

We describe our attempt to bring together System Dynamics and the Scenario Technique into a combined method. As a test case, we use the mini-world model developed by Bossel [5], which is a simplification of the much more sophisticated World2 and World3 models of Forrester [17] and Meadows et al. [18]. This world model contains three key drivers: consumption C, environmental damage ED, and population P. Bossel simulates this system's behavior using its nonlinear and ordinary differential equations description, but we will proceed with a simulation using only information gained in the scenario process. We assume a linear dynamic of a system with a different set of coefficients for positive and negative components in the state vector

$$x_{t+1} = A^{+}\mathrm{max}_c\left(\vec{0}, x_t\right) + A^{-}\mathrm{min}_c\left(\vec{0}, x_t\right), \quad (1)$$

with the componentwise minimum $\min_c$. An initial impulse $x_0 \in \mathbb{R}^3$ is given. The coordinates of the 3-vectors x_t represent the three key drivers C, ED, P. Below we describe how the entries of the 3×3-matrix A are obtained. The resulting scenarios will be verified by running the system's behavior through the standard scenario process of Gausemeier et al. [4].

For the development of our new method applied to the mini-world system, we made the following assumptions and simplifications:

- The key drivers' only projections are "rises 1%", "sinks 1%", or "remains (more or less) the same".
- The effect of a change in one key driver can have a maximum influence on the other drivers of $\pm 2\%$.
- All effects take place without a time lag.
- Impulses can only cause a $+1\%$, $\pm 0\%$ or -1% change in the key drivers.
- Impulses are unique events, at the beginning of the simulation in $t = 0$.

- There is a linear relationship between the key drivers.

After having made these simplifications, we developed a method which enhances the standard scenario process and adds aspects of System Dynamics thinking. The question is how to set up matrix A from the steps of the scenario process.

To simulate the system's behavior we need to estimate the influence of a change in one key driver on the other drivers. To characterize this influence, we have to be able to identify its magnitude and the direction (as in "$+$" or "$-$") of the influence. The direction of the influence follows from the definition of the key drivers from step 2 of the scenario process. As an initial step, we write down the following matrix, which we call *definition matrix*. It shows the direction of the effect that a change in one key driver has on the remaining key drivers.

definition matrix: key drivers	change	C	ED	P
C	$+$		direction of "$+$" change in C on ED	
	$-$		direction of "$-$" change in C on ED	
ED	$+$			
	$-$			
P	$+$			
	$-$			

Next we identify the magnitude of the effect on the key drivers by first completing a *direct influence matrix* as in Gausemeier et al. [4] using the scale:

0 = no influence,

1 = slight influence,

2 = medium influence,

3 = strong influence.

direct influence matrix	C	ED	P
C		direct influence of C on ED	
ED			
P			

For what follows, the direct influence matrix cannot be used. To enable us to estimate the strength of the effect of a change in one key driver on the others, we enhanced the direct influence matrix, again making use of the above scale of magnitude. The resulting matrix, the *enhanced direct influence matrix* depicts the magnitude of the reaction of the other key drivers to a $\pm1\%$ change in one key driver. Due to our simplifications, the possible impulses which effect a change in the key drivers are identical to the key driver's possible projections.

enhanced direct influence matrix		C	ED	P
C	$+1\%$		magnitude of reaction of ED to a $+1\%$ change in C	
	-1%		magnitude of reaction of ED to a -1% change in C	
ED	$+1\%$			
	-1%			
P	$+1\%$			
	-1%			

We now have two matrices, the definition matrix and the enhanced direct influence matrix. The first one contains data on the mathematical direction of the reaction of other key drivers to a change in one key driver, and the second one contains data on the magnitude of this reaction. We connect these two matrices into the *combined matrix*, which is the matrix A that we use for running a simulation of the system. From the simplifications we made, we developed a scale transforming estimations of strength of the reaction into percent (%) changes as follows:

0 = no influence = 0% change,

1 = slight influence = $\pm0.5\%$ change,

2 = medium influence = $\pm1\%$ change,

3 = strong influence = $\pm2\%$ change.

In the case of our mini-world model example [5], the combined matrix thus has the following shape.

combined matrix		C	ED	P
C	$+1\%$		$+1\%$	$\pm0\%$
	-1%		-1%	-0.5%
ED	$+1\%$	-0.5%		-0.5%
	-1%	$\pm0\%$		$+0.5\%$
P	$+1\%$	$+1\%$	$+2\%$	
	-1%	-0.5%	-0.5%	

3.2 Running the model

The combined matrix A is split up into the 3×3 matrices A^+ containing only the rows defining reactions to positive impulses, and A^- containing the rows defining reactions to negative impulses. The resulting matrices A^+, A^- are used to simulate the system's reaction to a number of external impulses or "shocks". Setting the value of all the key drivers to 1, these impulses could have an effect of +1%, -1% or no effect on the key drivers. To simulate simultaneous impulses on all the key drivers we defined an impulse vector.

$$x_0 := \text{impulse vector} := \begin{pmatrix} \text{impulse on } C \\ \text{impulse on } ED \\ \text{impulse on } P \end{pmatrix}$$

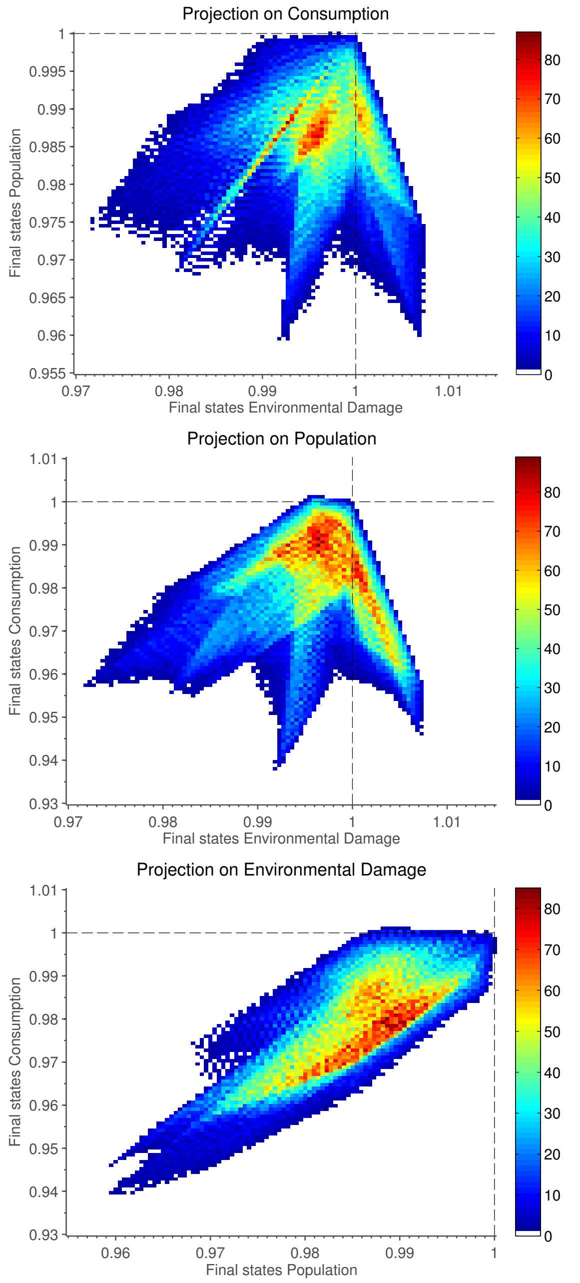

Figure 1: 2D projections of the final state vector space for $68,921$ impulses in $[-1,1]^3$.

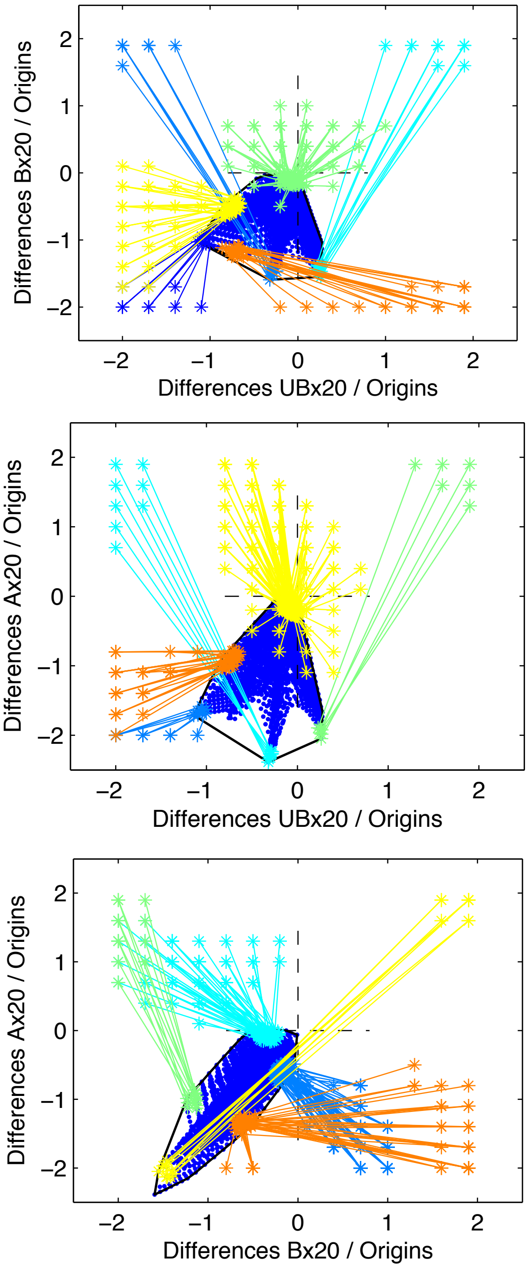

Figure 2: Clustering final state vectors from extremal scenarios.

An impulse vector $x_0 := (1,-1,0)^T$ would thus be interpreted as a positive $+1\%$ impulse of C, a negative -1% impulse of ED and no change of P. This initial impulse is simulated using the model's equation (1) for $t = 0, 1, \ldots$. This is a potentially infinite sequence of vectors x_t, that describe how the initial impulse is distributed through the system's key drivers. Actually, we see that after some iterations this impulse loses its momentum and vanishes, meaning that x_t is converging to the zero vector. For our mini-world data from above, we reached the computer floating point limit after at most 50 iterations.

To estimate the long-term effect of an initial impulse, we ask how the system has changed *because* of this initial impulse. That is, we integrate all intermediate vectors and reach a final *system shift vector* σ:

$$\sigma := \int_{t=0}^{\infty} x(t)dt \approx \lim_{T\to\infty} \frac{1}{T} \sum_{t=0}^{T} x_t.$$

For practical calculations, we evaluate the limit at the point $T = 50$, where the value of x_t has already fallen below computer floating point precision.

If we assume that in the beginning all key factors have a nominal value of 1, then the system is at first described by the *initial state vector* $\alpha := (1,1,1)^T$. Then the *final state vector* of the system is computed as $\Omega := \alpha + \sigma = (1,1,1)^T + \sigma$. For example, the above impulse vector $x_0 := (1,-1,0)^T$ leads in the simulation to $\sigma = (0.2, 0.5, -0.2)^T$, hence the final state of the system is $\Omega = (1.2, 1.5, 0.8)^T$. This means, that the initial impulse of $(1,-1,0)^T$ has a long-term effect on the system, so that C rises to 1.2, ED rises to 1.5 and P sinks to 0.8 units.

Since the model system has three key drivers and an impulse can have one of three effects on each key driver ($+1\%$, -1% or $\pm 0\%$) there are $3^3 = 27$ different impulse vectors. We use a fine discretization for the initial impulse vectors of 0.05 units, which results in $41^3 = 68,921$ different impulse vectors. The resulting final state vectors are be plotted in a graph (see Figure 1), which then allows to pool similar final state vectors to form scenarios (see Figure 2).

We identified six different clusters, depicted by different colors in Figure 2. The straight lines indicate the corresponding impulse vectors that can lead to a final state belonging to some cluster. In some cases there is only a narrow bandwidth for the impulses, and in other cases there is a large variety of different impulses that all lead to a final state in the same cluster.

3.3 Interpretation

The description and interpretation of the resulting scenarios will be omitted here. The mini-world model of [5] was run through the standard scenario process to create a number of consistent scenarios. A comparison of the enhanced method's scenarios and the standard method's scenarios shows us that the scenarios generated by the enhanced method are among those of the standard method which is to say the enhanced method generated consistent scenarios.

The enhanced method has a number of advantages. Whereas the standard method would interpret end values of driver C of $C = 1.01$ and $C = 1.1$ as "driver C rises", the enhanced model enables a more in-depth interpretation of the results. It creates scenarios in which the user can interpret the results of the driver's relative change. In the above example this would be "C rises only marginally" and "C rises drastically". To cover these possibilities, the standard scenario technique would have to define "C rises only marginally" and "C rises drastically" as projections for C, our enhanced technique covers these possibilities, and many others, automatically.

This result raises the question, whether the combined matrix A is able to substitute the consistency matrix with no detrimental effect on the scenario process. After all, both create consistent scenarios and the combined matrix allows a more in-depth interpretation of the resulting scenarios. If this were the case, the consistency analysis could be omitted, which would result in a quicker scenario process. True, instead of the consistency matrix one has to fill in the enhanced influence matrix, but it is usually easier to estimate the influence of one key driver on another than to estimate the consistency of two key driver's projections occurring at the same time.

To answer the question whether the consistency matrix can be replaced by the combined matrix, we must analyze in more depth what exactly each matrix stands for in the scenario process. The consistency matrix contains estimates of how well two projections of different key drivers "fit". By "fit" we mean how likely it is, that when one projection occurs the other will occur at the same time. An example of a highly consistent occurrence would be "rising population and rising environmental damage", an example of an inconsistent occurrence with a low consistency value would be "rising population and sinking environmental damage" (if we accept that more people cause more environmental damage). By estimating how likely various combinations of occurrences are, we are using intuition to evaluate how likely it is for various "blocks" to appear in a scenario. A "block" is a combination of two projections of different key drivers. By doing this for all the combinations of projections, we are forming a network within the system.

The combined matrix also relies on intuition but evaluates how strongly a projection of a key driver influences the remaining key drivers. By doing this, again a network is being created. This network also shapes the scenarios which result from the process. These two networks are "related" in that they both rely on intuition to shape the ties among the key drivers and their projections but they evaluate different aspects of these ties, namely one consistency and the other influence. If we accept that these are two aspects of the same system and that evaluations based on intuition are consistent in the sense that they do not change over time, then it is possible to replace the consistency matrix with the combined matrix.

This then results in a new process for creating scenarios. This process is based on the scenario process according to Gausemeier et al. [4], but is amplified by adding some aspects of System Dynamics.

4 OUTLOOK AND CONCLUSIONS

It is our ongoing research to analyze whether these steps are applicable for other Scenario Technique applications, and how to formulate the initial simplifications and assumptions. Should these be removed, the new method must be slightly altered. Some simplifications are easily removed and even have a positive effect on the simulation by making it more realistic and more dynamic, e.g. including more than three key drivers, incorporating time lag of effects and allowing several impulses to take place over time.

In general, problems arise with the categorization of key driver's projections. Not all drivers can be described numerically in the form of "rises/ falls x%". For example, how would one interpret "protectionism" as a projection of the key driver "development of global trade"? One possible solution would be to describe these types of key drives qualitatively and simply estimate the strength of this projection and its direction of influence on the other key drivers, limiting the range of maximum effect to the standard $\pm 2\%$. These drivers, which cannot be described quantitatively could thus be integrated into the combined matrix and the simulation. In the same way, impulses of, say $+1\%$ can be interpreted not as "1% more protectionism" but rather "more or stronger developments towards protectionism". Taking both these adaptations into account, one can incorporate quantitative key drivers into the simulation and the impulses.

This paper laid the foundation for the development of a new scenario technique. The Scenario Technique based on Gausemeier et al. [4] was amplified by adding aspects of System Dynamics into the scenario creation process. This leads to a more in-depth and varied interpretation of scenarios. The new process was developed using a mini-world model consisting of three key drivers. Several simplifications were made during the process. The process was formalized in a step by step instruction. We demonstrated how to apply our new method to a small mini-world example of Bossel [5]. In our future research we aim to apply our new method to a larger Scenario Technique application.

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