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Modeling & Simulation for an Investigation Process to support Decision Making in a Non-Ordinary Context

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Abstract

This paper presents an innovative solution to enhance the decision-making process for the feasibility analysis of an industrial plant using the Strategic Engineering paradigm. The research highlights the potential of this paradigm to model and simulate the interconnections between economic, social, and engineering fields, thereby supporting decision makers. The project utilized Modeling & Simulation, Artificial Intelligence, and Data Analytics to understand the complex scenario of constructing an industrial plant for essential medicines in the post-conflict territory of Iraqi Kurdistan. The study aims to demonstrate the effectiveness of Strategic Engineering in conducting a cost-benefit analysis for a new industrial site in a non-ordinary context. This research opens the field for future studies and implementations using hybrid simulation methodologies for decision-makers' courses of action.

Keywords: Strategic Engineering, system dynamics, human behavior modeling, cost-benefit analysis, decision support

1. Introduction and background

Employing Modeling and Simulation (M&S) to tackle complex problems and systems is a well-established technique with strong potential for decision-making (Banks, 1998). According to the perspective of Strategic Engineering, any country is considered as a set of complex systems, a sort of System of Systems (SoS) to which multiple and changing variables refer to be considered, organized, and managed (Bruzzone et al., 2018a).

A system is a set of interacting elements organized to achieve one or more stated purposes, which would not be obtainable by the simple sum of the individual elements alone, “a whole that cannot be divided into independent parts” (Backlund, 2000).

Simple systems have a limited number of components that interact in a predictable and linear manner. Complicated systems, although intricate and detailed, are theoretically fully understood; it contains variables which combine in linear ways and their effect is knowable. Chaotic systems are governed by non-linear relationship where small changes in initial conditions could result in drastically different and seemingly random outcomes over time, with behavior highly sensitive to initial perturbations (a phenomenon often described by the butterfly effect). The system may be deterministic in some choices of the parameters but chaotic in other regions (Norman, 2011). Finally, complex systems are systems composed of many interacting components, which may exhibit collective behaviors and properties not predictable from the properties of the individual components alone.

These systems are characterized by emergent properties, nonlinearity, and often demonstrate behaviors that cannot be easily deduced by examining their parts in isolation. Complexity in these systems arises from the interdependencies and feedback loops among the components, which lead to unpredictable and dynamic behavior (Ladyman et al., 2013; Ottino, 2003).

Complexity in systems refers to the emergent properties that arise from the interactions within a system's components, leading to behaviors and characteristics not evident when examining the individual parts alone. Some studies explore complexity across physical, living, and mathematical systems, highlighting how interconnected components create intricate patterns and behaviors (Lacasa, 2009).

The complex system of a country is therefore tackled, for example, to prevent disasters and manage emergencies (Bruzzone ed al., 2018b), to manage critical infrastructures (Bruzzone ed al., 2018c), to support their reconstruction (Bruzzone ed al., 2011), as well as to estimate the impact and repercussions on operations or investments (Bruzzone ed al., 2013).

As wonderful as the human mind is, the complexity of the world, often defined in terms of the number or links between elements of a system or the dimensionality of a research space, diminishes and limits our understanding, and our ability to comprehend evolving impacts is quite limited. In a world where the complexity of the social system and change are constantly accelerating, with unforeseen side effects and with decisions hindered by policy resistance, understood as the tendency of interventions to be defeated by the system's response to the intervention itself, the solution is found in system thinking, that is, in the ability to see the world as a complex system and to understand how everything is connected and interconnected to everything else (Sterman, 2000). To understand the sources of political resistance, we must therefore understand both the complexity of systems and the mental models of those systems that we use to make decisions. Systems have a high combinatorial complexity, which, although present with modest intensity in simple systems, could generate dynamic complexity. In fact, most cases of policy resistance stem from dynamic complexity, the often-counterintuitive behavior of complex systems that emerges from agent interactions over time (Simon, 1969; Sterman, 2002).

Although there is no universally defined model to fix the dynamics involved in a post-conflict process, the model presented intends to provide information to decision-makers who evaluate an industrial investment in the Non-Ordinary Context as a Complex System (NOCaaCS). This study offers a step towards developing such a capability by describing a model to simulate a business project in a post-conflict environment.

In their complexity, human systems present unique challenges with long time horizons, issues that cross disciplinary boundaries, the need to develop reliable models of human behavior, and the great difficulty of experimentation. To achieve effective change in social systems, the active participation of a wide range of experiences in the process of modeling and decision construction is therefore necessary (Sterman, 2002).

To be effective, Strategic Engineering considers the social, political, environmental, and other impacts of solutions, envisioned with interdisciplinary applications that also make use of the input of cognitive and social psychology, organization theory, economics, and other social sciences. A holistic view allow us to learn faster and more effectively, identify any critical leverage points and avoid political resistance, and make coherent decisions.

With this in mind, this article deals with the dimension of complex systems and some requirements and steps for the use of system dynamics, illustrating its application to a business issue.

The study starts from an in-depth analysis of data and information to search for the characteristics of interest and represent the nature of a logical procedure that offers a simulation in terms of macro-cost-benefit analysis and social sustainability of a complex system that intertwines economic-social variables with models of human behavior of the population and obtain outcomes to support decision-makers. This translates into a process of graphic schematization and implementation of a model that allows you to obtain results and design scenarios useful to the decision-maker. The simulation approach developed with the System Dynamics (SD) method (Forrester, 1961 and 1969) using the AnyLogic software represents the macro-level sought, leaving the implementation of the model to future in-depth studies.

2. System Dynamics approach

In order to retrieve data, it was necessary to carry out an in-depth analysis of the sources through institutional websites, international annual reports, open data and targeted surveys, together with an archiving of the relevant data to identify the characteristics and input factors for the simulation.

Data Analytics process was carried out through a specific method and procedure. In facts, historical data are recorded in different ways depending on the available and found sources, and this causes errors during recording on computer systems; therefore, filtering, and eventual merging of the data was necessary to avoid errors and missing data. This was particularly true for demographic findings, social categories, level of education, family, ethnicity, migration flows, IDPs, health, economic data, etc., where there may be discrepancies, mismatches, errors or omissions between different sources.

Then the data are merged with the process information to allow the simulator to manage the information, applying the necessary filters and processing.

In order to increase the awareness of the possible outcomes of the investment and to improve the solution, it is necessary to have reliable models able to quantitatively estimate the impact of the variables considered (Bruzzone, 2013; Bruzzone et al., 2018b) for a more realistic cost-benefit analysis.

SD models represent social systems as webs of level values and rates of change interconnected by nonlinear relationships, information feedback loops, and time delays (Lane, 1997). Once our model representing the complex system of interest is built, simulation is used as "the means of inferring the time evolutionary dynamics endogenously created by such system structures".

SD methods are well suited for the simulation of complex social systems, such as the functioning of an organization or a government, the dynamics of international development as well as for economic intervention in an unconventional area (Forrester, 1961). For this reason, the present research is interested in the possibility of a systems dynamics model providing an adequate capacity for modelling and analysis of an intervention in a post-conflict country.

3. General architecture

SD, invented in the late 1950s by Jay Forrester, is a technique for strategic modeling and policy simulation based on feedback systems theory. Since then, it has developed as its own field, distinct from the broader fields of operations research and management science to which it is related.

One of the main reasons for applying SD to industrial designs is its ability to capture and explain system behavior and its temporal variations (Wolstenholme, 1990). In SD components, the feedback function is unavoidable; these features are represented by Causal Loop Diagrams (CLDs) in the structure and are useful for analyzing the causes of dynamics and creating communication between variables.

In CLDs, positive and negative signs are described as reinforcement and balancing, respectively. By reinforcement cycles, we mean the increase in the effect variable when the source variable increases, and balance cycles lead to a decrease in the effect variable when the source variable increases. Although CLDs are part of the system dynamics approach, they are valuable tools for presenting and showcasing the feedback structure of complex systems with their components and behavioral patterns.

We then proceed with the creation of the basic structure of the SD model, starting from the identification of the macro-variables and the relationships between them, to continue with the collection of the data of interest and the creation of the CLD. The review of the literature on the subject allows us to know the degree of in-depth analysis on similar contexts (on industrial plant engineering and on the contextualization of the post-conflict area) and to identify the risk factors that is shared for the case study (Choucri et l., 2004; Richardson et al., 2004). Before the evaluation part, alternative options are identified, intervening on the variables that could influence the scenarios (Course of Action).

The qualitative approach, focused on the deep immersion of the evaluator in the local context, aims to obtain an in-depth and contextualized understanding of the system, also allowing a different reading of the data and information found from public and official sources, enriching the feasibility study, and allowing the decision-maker to analyze and make informed and sustainable decisions both from a cost-benefit point of view and from a social point of view. The PEST (Strengths, Weaknesses, Opportunities, Threats), SWOT (Political, Economic, Social, Technological) and MCDM (Multi-Criteria Decision Making) analysis methods are undoubtedly excellent approaches to the problem, but they do not have the quantitative condition we are looking for and above all they are not useful in the case of problems that need to be addressed with non-linear programming and with emergent behaviors that are expected.

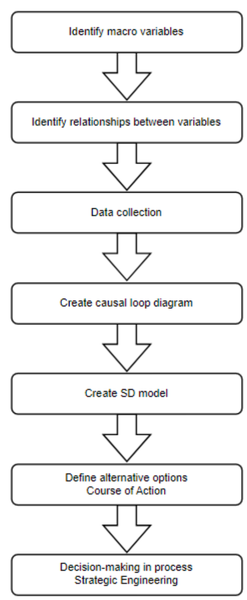

Fig. 1 Process roadmap

We start from a high-level conceptual framework to understand the situation in a macroscopic way and define all the main actors potentially involved in the problem. Taken as a whole, the case study system appears complex in its nature and requires the work of an interdisciplinary team of experts to carry out a complete and exhaustive analysis, with specific skills and knowledge in each area.

In this study, a part of the conceptual model is analyzed and for this purpose some causal loop diagrams are constructed to indicate the interactions between the variables and the impacts produced: the model clarifies the problems and facilitates a holistic understanding of the investment project in its context.

In the diagrams, the "+" marks on the arrowheads indicate that the effect is positively related to the cause (an increase/decrease in variable A leads to an increase/decrease in variable B), the "-" signs indicate the opposite, "R" indicates a ring reinforcement of the loop.

In Fig. 2 the reinforcement loop, R_4 (self-reinforcing), illustrates the "exponential growth" behavior of a group of components related to the tax system.

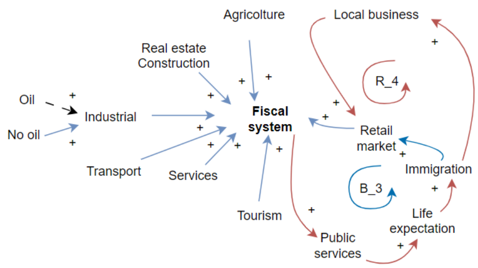

Fig. 2 – Fiscal subsystem

An increase in non-oil industrial production leads to an increase in tax revenues, particularly in terms of taxes and local revenues. Due to the benefits of the implementation of the industrial project, the number of consumer staples (and consumers) increases significantly and contribute to increasing the money of the local budget. In addition, with the improvement of public services, there is the potential for a new trend of expansion and development of the province's outer areas (untapped rural areas) that increase the construction sector with the possibility of new residential developments. An increase in immigration causes a "positive" change in production; in this way, the positive effect in the R_4 loop is reinforced. In addition to the R_4 loop, the B_3 loop (balancing) reflects the relationship between the economic system, public services, life expectancy, immigration, and the retail market.

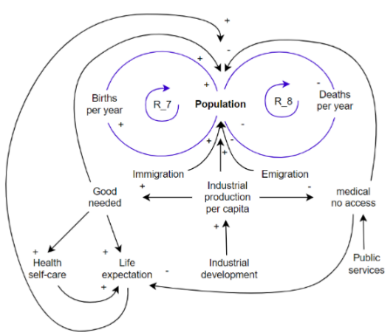

Fig. 3 – Population subsystem

Industrial development allows us to improve per capita production (Fig. 3), which influences the population (and human behavior) by increasing its well-being and with it births, as highlighted by the R_7 reinforcement loop; at the same time, it responds positively to the need for basic goods, indirectly improving the population's self-care and life expectancy, which are directly correlated with growth. Otherwise, the reinforcement loop R_8 demonstrates that the lack of access to medicines negatively affects the population, generating an increase in deaths.

After designing the causal diagrams subsystems, we combine these loops with all other factors within a cost-benefit analysis system to provide a holistic picture of the impact of the project in its context and observe the relationships and feedback processes between project components. Once you have created the CLD, the next step is to use it to create a quantitative stock-flow model that covers the same set of relationships. The population value (initialPOP) has been identified as an initial variable, as it is a value extracted from the literature (official website of the Government of the autonomous region of Kurdistan) and is considered crucial for the functioning of the various loops constructed, as it is based on this data. Once the functioning of the individual subsystem has been verified, they were connected to create the basic model that involves the simulation of the features of interest for subsequent analysis. To simplify the model, some known parameters and starting variables were considered and used and obtained from the data found, which were subsequently considered as a reference for the projections developed. For the analysis, a time horizon was therefore defined as 30 years for the projection of the cost-benefit examination on the investment, considering the average life of a production plant.

4. Model implementation

As a starting parameter, reference is made to the current population (initialPOP) and its growth over time is estimated. A comparison with the data available in the literature shows an estimated projection from 2020 to 2040 of a gradual increase in the population from the current 6.6 million inhabitants to 8.8 million towards the end of the next twenty years, assuming an average fertility ratio of 2.8 (3.1÷2.5) and considering a population growth index of 1.82%, as indicated in the Population Analysis Report published by KRI (Kurdistan Region of Iraq) in February 2021. Lifetime is considered to be an average between the sexes and equal to 75.2 years in 2020, with a projection of an average of 79.2 years in 2040. Another important projection parameter in the industrial context (relating exclusively to the non-oil industry sector) is the GDP of the area of interest. This parameter is also influenced by various internal and external factors, but for the sake of simplification it has been assumed that it is exempt from it. In addition, for the model it was assumed to consider the GDP of the non-oil industrial sector only, taking as a reference that relating to the industries considered "big" (Kurdistan Region Government, 2020).The input GDP is considered to be the sum of all the production systems present.

$$GDP_{in} = \sum_1^n Q_{in} P_{in} \quad (1)$$

GDP is linked to regional non-oil industrial revenues through a coefficient that normalizes national data (initial GDP), which is then linked to the population stock (POP) through the birth flow.

$$P(t) = \int_{t_0}^{t_n} [P_{gr}(t) \times P(t-1)]dt + P(t_0) \quad (2)$$

By running, it is possible to check the compatibility between the results and the statistical predictions, for example in the case of deaths.

$$Deaths = POP \times deathrate + POP \,/\, lifetime \quad (3)$$

Since we do not even have up-to-date data on the revenues of the non-oil manufacturing sector, the turnover of the sector was estimated (Kurdistan Region Government, 2016) and its growth rate (industrygrowthrate) was deducted from the statistics relating to the last available time period (UNESCO, 2019), introducing the growth parameter due to new production and the revenue's tax system,

$$Ind._{gr} = 0.015 \times Ind.rev + Drugs\ demand \,/\, k_2 \quad (4)$$

$$Initial\ GDP = Industry_{non\ oil} \times k_3 \,/\, 10^9 \quad (5)$$

$$Ind.rev\ (t) = Ind.rev\ (0) + \int_{t_0}^{t_n} (Incr.Ind.rev)dt \quad (6)$$

where k_2 and k_3 are empirically validated constants.

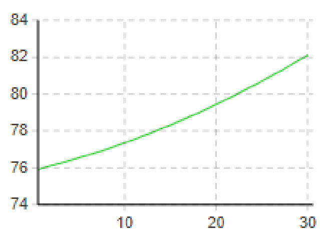

Fig. 4 - Life expectancy outcome

5. Results and discussion

The formulas used to calculate the output values allow us to appreciate an estimate of what could happen in terms of population growth, and therefore GDP per capita, allowing for better and greater availability and purchasing power and at the same time an increase in productivity. This aspect is validated by the analysis of the Consumer Price Index, according to which from the value of -10.3 referred to 2012 in Kurdistan there has been an oscillating trend, with a decrease in the period of the war against ISIS and Covid-19, up to a constant growth starting from 2020 reaching a value of 10.9 in 2022, with a growth rate between 2019 and 2020 of 7.6% and 7.1% between 2020 and 2022 (Kurdistan Region Government, 2023). In addition, considering the average purchasing power index according to the main sections of the product basket for the year 2022, it appears that for the "health" sector the population has reached the value of 123.1 (on a 100 basis), highlighting a growing interest in it. By running the model and examining the results expressed on the plots, it is possible to carry out a first comparative analysis on the effectiveness of the model and on the reliability of the data entered and the formulas used. It should be noted that population growth responds to the KRG's (Kurdistan Region Government) statistical forecasts according to which there should be a progressive growth over the next twenty years corresponding to an average of 1.82%, recording a value of 8.850 million inhabitants in 2040. Also, with regard to the variable of life expectancy, its growth, recorded with a starting average of 75.2 years in 2020, leads to an expected twenty-year value of about 79 years, very close to the statistically expected value of 79.2 from the KRG data. This information allows us to understand the trend of industrial production, as it is directly connected with the medical good required (goodneeded) and indirectly with public services, through which the population receives more attention and therefore extends life expectancy (lifetime). In addition, industrial production affects regional and national GDP, allowing the growth of the non-oil industry sector, helping the country to free itself from the condition of "rentier economy" on which it depends, interpreting the country's development potential through new forms of economy. The expected trend is also observed for births and immigration confirms the interest in a better quality of life, while for public services the growth, which derives from new tax revenues, stabilizes over time in correlation with the same revenues. From an economic viewpoint, the benefits linked to the project derive mainly from the revenues deriving from the investment, which creates a new workforce and social development, and from the tax contribution of the various industrial sectors involved. All estimated project benefits at different times must be discounted to current values before comparing them to project costs in the initial phase. The macro-cost-benefit analysis is identified using the total present values of the project benefits minus the total costs of the project. The value of the analysis has accumulated over time, and when it reaches zero (Fig. 5) it means that the total benefits are equal to the total cost. In other words, the payback period has been identified as the 1time point at which the NPV is zero.

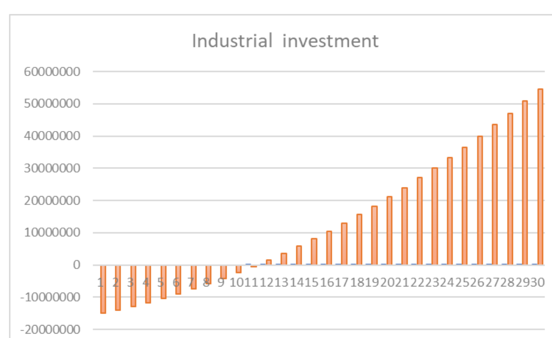

Fig. 5 – Estimated economic return

6. Conclusion

By applying Strategic Engineering, we wanted to highlight how with simulation it is possible to understand the effects of decisions before implementing and applying them in the reality, allowing to evaluate the influences of the variables involved and their impact, to identify undesirable scenarios in advance, and to exploit emerging opportunities by improving risk management. This makes it possible to reduce uncertainties in the face of an analysis and investment process, allowing to recognize its evolution in terms of economic feasibility, sustainability, and social impact.

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