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SOFT SYSTEMS METHODOLOGY AS A SYSTEMIC APPROACH TO NUCLEAR SAFETY MANAGEMENT

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ABSTRACT

Safety approach currently adopted by nuclear installations is built almost exclusively upon analytical methodologies based, mainly, on the belief that the properties of a system, such as its safety, are given by its constituent parts. This approach, however, doesn't properly address the complex dynamic interactions between technical, human and organizational factors occurring within and outside the organization. After the accident at Fukushima Daiichi nuclear power plant in March 2011, experts of the International Atomic Energy Agency (IAEA) recommended a systemic approach as a complementary perspective to nuclear safety. The aim of this paper is to present an overview of the systems thinking approach and its potential use for structuring sociotechnical problems involved in the safety of nuclear installations, highlighting the methodologies related to the soft systems thinking, in particular the Soft Systems Methodology (SSM). The implementation of a systemic approach may thus result in a more holistic picture of the system by the complex dynamic interactions between technical, human and organizational factors.

1. INTRODUCTION

Many of the problems affecting the safety of the nuclear installations result from the dynamic interaction between human, technological and organizational factors. These complex problems represent an almost insurmountable challenge to the traditional analytical approach, commonly used for safety analysis of nuclear installations. In the analytical approach the problems are reduced in size by analysis to a set of simpler problems, these are then solved and their solutions are assembled into a solution to the total problem. This approach generally pays most attention to technological factors ("physical barriers"), where all interactions between engineering systems, equipment and components are reduced by analysis to the fundamental relationship, cause-effect. The analytical approach has been useful in many of the problems involving the safety of nuclear facilities.

However, after the accident at TEPCO's Fukushima Daiichi nuclear power plant (NPP) in March 2011, it became apparent that the current "reductionist" nuclear safety analytical approach, in which systems are split into smaller parts to make it manageable and to ensure that nothing is left unattended, was not enough [1-2]. In fact, some studies point to the interaction between failures involving human and organizational factors such as a) communication; b) training; c) decision making; d) preparation for the unexpected; e) understanding of organizational interdependencies; and f) design or technology; as the main contributor to the Fukushima Daiichi accident [1-2].

On the other hand, since the 1970's, problems of a similar nature named as wicked problems or messes have been addressed within soft systems thinking by qualitative and interpretive methodologies such as soft systems methodology (SSM) [3].

This paper aims to describe the SSM, as designed by Peter Checkland [4-7], and to demonstrate its potential utility in the treatment of complex problems affecting the safety of nuclear installations, especially those problems that involve the dynamic interaction between human, technological and organizational factors.

2. SYSTEMS THINKING: HISTORY OF THE DEVELOPMENT

Systems thinking, understood as a holistic view of the world, has followed humanity for thousands of years. Manifestations of this kind are observed in Buddhism from oral traditions of the Dhama; in the Hindu spiritual traditions from the Vedas writings, especially in the Upanishads and Bhagavad Gita; in Taoism with the holistic view of medicine; in Sofi-Islamism; and in Greek philosophy through the constantly changing world view of Heraclitus and Aristotle's hierarchical view of the nature [8].

In the twentieth century, the term systems thinking has been widely used by different scientific branches, so that there are different and sometimes incompatible definitions of it. However, all those branches agree on one point: that the systems thinking is a holistic approach, that seeks to understand the world as an inseparable whole, opposing to the reductionism of the classical science [9]. Nowadays systems thinking is known as a discipline with applications in many other disciplines, such as those related to the exact, biological, and human sciences [10].

Numerous authors have thought different perspectives to describe systems thinking, focusing on their main thinkers and schools of thought, their variety of philosophical paradigms, metaphors, social theory, or on the variety of problematic situations they deal with [11]. However in this work the metaphor of the three waves was used to explain the successive developments of systems thinking as proposed by Gerald Midgley [12]. Each wave throws useful materials to the beach, and then refluxes leaving some materials back to the beach, while others return to the sea to be rearranged and added to other materials on the sea, that will be thrown back to the beach when the next wave hits.

2.1 The First wave of Systems Thinking: The Hard Systems Thinking

The first wave of systems thinking, also known as hard systems thinking, emerged in the 1940s and 1950s from the development of the general systems theory (GST) and cybernetics and received widespread popularity in the 1950s and 1960s [9,12].

GST has received significant attention with the dissemination of pioneering Works of von Bertalanffy published in 1956 [13]. Other key authors for the consolidation of this approach were Boulding and Sttaford Bee. GST doesn’t seek to solve the problems or try to provide practical solutions, but to produce conceptual theories and formulations that create the conditions for the application in the empirical reality.

GST defends that systems have some general properties, common to all of them, that can be described by mathematics. According to GST, systems are understood as open systems, maintaining a continuous exchange of material-energy-information with the environment. GST makes it clear, therefore, that three aspects must be considered in an organization's assessment: a) the necessity to consider it as a whole and not just as individual departments or sectors; b) the identification of external and internal variables that, in some way, may influence its functioning; c) feedback loops that operate within the organization [14].

Cybernetics, also known as communication and control theory, was the first discipline to benefit from concepts of GST, particularly the concept of open systems and feedback. Cybernetics has as its main focus the self-regulation of the systems, which is done by receiving and processing output information about the system's situation and then inputting that information into the system so that it corrects errors (feedback). Some the key authors of the beginnings of cybernetics are Weiner, Ashby and Bateson [14-15].

There are several cybernetics-based methodologies that provide mathematical modeling tools, including the Systems Engineering, Systems Analysis, and System Dynamics. The latter, conceived by Jay Forrester in 1961 [16], provides evaluators with a useful quantitative tool for modeling complex feedback processes [14-15].

From late 1960's to early 1980 the hard systems thinking was criticized about the philosophical assumptions and the consequences of its practical application [9,12,17]. The main critique came from the fact that the authors of the hard systems thinking saw the world as a set of inter-relating systems that could be reengineered in order to be improved and that they considered their models as exact representations of reality and not as the aid for the development of their intersubjective understanding. People, when included in their models, were treated as components of a large machine that needed to be adapted, so that the system as a whole could work optimally. Another critique came from the practical field, when it was found that the models that seemed to work well in some situations failed when considering social complex situations [9,12,17].

2.2. The Second Wave of Systems Thinking: The Soft Systems Thinking

The second wave of system thinking, also known as soft systems thinking, came around 1970 from the criticisms made by the hard systems thinking. Churchman [18], Ackoff [14] and Checkland [4], were the pioneering authors who contributed decisively to the paradigm shift. The consolidation of this new paradigm came mainly from new theoretical developments and applications, mainly from the UK, produced by authors like Checkland, Jackson, Mingley, Flood, Mingers and Keys, among others [9,12,17].

In the soft systems thinking, the world is seen as a complex and confusing entity that can be explored through a systemic process, organized as a learning system. Therefore, the "systems" are no longer seen as real-world entities, but constructs capable of helping to understand the complex and non-structured problem situation. Emphasis was placed on: a) dialogue; b) mutual appreciation; c) intersubjective construction of understandings; d) search of accommodation between the different perspectives [9,17,19-20].

2.3 The Third Wave of Systems Thinking: Critical Systems Thinking

Finally, starting from the 1980s, a new wave of systems thinking emerged, known as "critical systems thinking", and whose manifestations are still noticed. [10,12,14,17]. In many ways, critical systems thinking can be seen as an extension of the soft systems thinking.

Two main aspects characterize the critical systems thinking movement: a) the critical discussion on the limitations of soft systems thinking, especially regarding the treatment given to the relations of power and coercion [9,12,17]; and b) the development of criteria that consistently allow the use of more than one method or methodology, methodological pluralism, in order to improve the problem situation. Different types of methods focus on specific aspects of a problem situation, so employing more than one method in combination will help address different aspects of a situation [9,21-24].

3. PROBLEM STRUCTURING METHODS - PSMs

Within the paradigm of the soft systems thinking, a group of interactive and participatory modeling approaches called Problem Structuring Methods (PSMs) was developed. The PSM's main objective is to help groups of people with different points of view to understand complex and problematic situations of common interest. Therefore, it is not intended to solve them, although many times they are used for this purpose [25].

Some of the main characteristics of PSMs are: a) they follow systems approach; b) the constructed models are mainly qualitative; c) they are simple and transparent, seeking to clarify the terms of conflicts; d) they allow various perspectives of the same problem to be considered; e) they are easily understood by users, who can often come from quite different areas of knowledge; f) they operated iteratively [25].

The most well-known PSMs are Soft Systems Methodology (SSM), Strategic Options Development and Analysis (SODA) [26], Strategic Choice Approach (SCA) [27], Robustness Analysis, Drama Theory, Viable Systems Model (VSM), Metagame, and Hypergame Modeling. According to a survey carried out by Mingers in 2009 [20] through ISI Web of Science (WoS), Scopus and Google Scholar (GS), the first three, in order, SSM, SODA and SCA, were the PSMs with the highest number of occurrences [20]. Other systems approach similar to the PSMs worth mentioning are Ackoff's interactive planning, Churchman's social systems design, and Mason and Mitroff's strategic assumption surfacing and testing.

The following are brief descriptions of SODA and SCA. The Soft Systems Methodology (SSM) because of its range, methodological consistency, popularity and potential to be used in complex problems involving nuclear safety, will receive special attention in this paper, thus being developed in a separate section.

3.1 Strategic Options Development and Analysis - SODA

The SODA method was conceived in the late 1980s by Colin Eden [26]. The key aim of SODA is to structure complex problems and to achieve understanding and agreement among the group members regarding the problem under discussion. Currently, this method is widely used as a strategic planning tool both to identify organizational goals, as for decision options.

The application of the SODA method is focused on the elaboration of graphical representations, namely cognitive maps, that try to capture the perception, reasoning and judgment of an individual or group about a certain problem situation [28].

The application of the SODA method starts with the choice of the members that will make part of the work group that aims at structuring and improving a given problem situation. After that, all of the chosen people are interviewed in a relatively unstructured way to try and elicit their thoughts about the problem under discussion. From this discussion cognitive maps are drawn to help each individual refine their thinking. As soon as all the cognitive maps have been developed, they are merged into a single map that can initially contain several hundred concepts. Similar concepts are then merged into one while keeping concepts from key members of the group and maintaining a balance of concepts from all members of the group. Finally, this map is validated and the consensual actions are defined after the realisation of workshops [25].

3.2 Strategic Choice Approach – SCA

The SCA was designed by Friend and his colleagues in the late 1980s [27]. SCA is a planning approach centered on managing uncertainty in strategic situations. In SCA there are three key elements of analysis which are used in structuring problems: a) the decision area where an alternative course of action is possible; the comparison area where each of the feasible decision schemes are compared and ranked; and c) the uncertainty area where the problematic situation is examined, generally in interactive workshops, considering three areas of uncertainty: i) uncertainty associated with the working environment, which can be dealt with using methods from the quantitative applied sciences; ii) uncertainty associated with values, that can be treated through the examination of "politics" and; iii) uncertainties associated with the related decision fields, which require the analysis of the relationships between the decision being discussed and other strategic and organizational priorities, often involving the multi-agency working. According to Friend, after examining the three types of uncertainty, priorities will emerge and the appropriate paths for analysis may be then chosen 25,27].

4. SOFT SYSTEMS METHODOLOGY (SSM)

SSM was developed by Peter Checkland and colleagues at the University of Lancaster Systems Department, in the late 1960's, to model organizational processes involving problematic situations where there are divergent views about the definition of a problem. Checkland defines his methodology as: *"Soft Systems Methodology (SSM) is a cyclic learning system which uses models of human activity to explore with the actors in the real world problem situation, their perceptions of that situation and their readiness to decide upon purposeful action which accommodates different actor's perceptions, judgments and values"* [4].

The basic concepts of SSM were first presented in 1981 in the book Systems Thinking, Systems Practice [4]. However, the experience acquired with numerous practical applications allowed SSM to pass through successive improvements [4-7]. From its original design that involved a seven-stage intervention process, SSM turned itself in 2006 into a more flexible

and sophisticated process, as described in Checkland's most recent book, Learning for Action [7], describes the improved methodology as a process of four main phases: Finding Out; Making Purposeful Activity Models; Using Models to Structure Discussion about the Situation and its Improvement and; Defining 'Action to Improve'. However, it is important to note that Checkland repeatedly emphasizes that SSM is neither a formula, nor a method or technique, but a set of methodological principles. The method used will be different for each problem situation. In addition, Checkland also emphasizes that the phases and steps advocated by the methodology should not be mechanically implemented in a linear sequence, but, instead, should be in harmony with all the others phases and steps. The four phases suggested by Checkland in the latest version of its methodology are summarized below.

4.1 Finding Out

Checkland identifies four ways of finding out about the problem situation. They are: 3 ways of analysis (Analysis One, Two and Three) and rich pictures. These four ways are described in more detail in the sections below.

4.1.1 Analysis one (the intervention itself)

This analysis is concerned with examining the people in the situation in terms of roles rather than individuals. According to Checkland, when SSM is used to improve a problematic situation, there are three elements: the methodology; the use of the methodology by the practitioner and the situation [6-7]. These elements are determinant to the intervention process' success. Therefore, it is useful to identify three key roles in an intervention: a) the 'client' (who caused the intervention to happen); b) the 'practitioner' (who would conduct the investigation); and c) the 'owners' of the addressed issues (who are defined as those affected by the intervention). Practitioners are encouraged to include themselves in the list of 'issue owners'.

4.1.2 Analysis two (social): This analysis is concerned with investigating the culture of the problem situation under examination. Here, culture is understood as the "social texture of a human situation" and is seen to involve the interaction between Roles, Norms and Values. Roles are the social positions that mark the differences between members of a group. Norms are the expected behaviour associated with the roles. Values are the criteria by which the behaviour within a role is judged [6-7].

4.1.3 Analysis three (political): According to Checkland [6,7], this analysis asks: How is power expressed in this situation? This is tackled through the metaphor of a 'commodities' of power in the situation, how they are exercised and how they may be contained (checks and balances). Examples of commodities are personal charisma, access to important authorities, access to important information, having intellectual authority and reputation, etc.

The politics of a situation just like the social context as explained above are decisive to understand in order to identify changes that are both desirable and culturally feasible to be implemented in the latter stages of the process of intervention using SSM.

4.1.4 Making rich pictures

Rich pictures are pictures that try to represent the vision that each stakeholder has the problematic situation. Once elaborated they provide a discussion platform that helps users to understand the relationships within the problematic situation - how they are generated and how they act - and to identify new relationships not previously perceived. This picture will become "richer" as the perception of the problem situation (as seen by each stakeholder) is improved through interviews, meetings, document reading, etc. According to Checkland and Poulter, the purpose of elaborating a rich picture is "…capture the main entities, structures and viewpoints in the situation, the process going on, the current recognised issues and any potential ones" [7]. An important feature, also emphasized by Checkland, is that rich pictures overcome the limitations and assumptions that abound in language and avoid imposing a particular structure on the overall view of the problem situation [4].

Having already run Analysis One, Two and Three as well as the rich picture, the problem situation is discussed in a workshop with the intervention team and a list of concerns surrounding the problem situation is elaborated. This list will be the starting point for the next phase of the process of intervention involving SSM.

4.2 Making Purposeful Activity Models [4-7]

This phase begins with the set of concerns (elements of the overall problem situation that are deemed to be relevant for further analysis) identified in the previous phase. These concerns are examined one by one and assembled in groups that have some similarity. Each of these groups of concerns constitutes a relevant system. The concerns within each relevant system, often defined in an imprecise and ambiguous way, are rewritten in a clear and precise form and are renamed "root definitions". The process involving the transition from inaccurate to precise is aided by the acronym CATWOE, the client (C), actor (A), transformation (T), Weltanschauung (W), Owner (O), Environmental constraints and by the PQR formula.

Each root definition should make explicit the particular viewpoint, Weltanschauung (W), and the Transformation Process (T) that takes a certain condition from an undesired state to the desired state (purposeful activity). It will require people (A) to perform the activities comprising T and will affect people (C) who will be either beneficiaries or victims of those activities. The activity will be constrained by the environment (E) and can be stopped or changed by some person(s) who are regarded as 'owners' (O) of the activity. Besides that, it also has to be described what the system does (P), how (Q) and why (R) it should be done (PQR formula). The Root Definition should capture all the CATWOE elements to facilitate model building incorporating PQR. Thus, each root definition provides an encapsulation of the problem situation, viewed from a particular perspective, and is the central component of the collective activities that are portrayed in the rich figures.

For each root definition a purposeful activity model is built. This model is usually represented in graph form, where the logical dependencies between the activities required to promote the transformation described in root definition are identified. Activities that monitor and control this transformation process are also included. The criteria commonly used in this control are: a) effectiveness: which identifies if the transformation is working or producing the desired results; b) efficiency: which verifies if the transformation is being achieved with the minimal use of resources.

4.3 Using Models to Structure Discussion about the Situation and its Improvement

In this phase each of the purposeful activity models is confronted with the real world, specially using the rich pictures and Analysis One, Two and Three, carried out in the first phase of the process [4-7].

4.4 Defining 'Action to Improve'

It is fundamental to understand that the discussion phase in the SSM does not seek to obtain consensus, but rather the accommodation in relation to the solutions, that is, a solution that everyone can live with. According to Checkland, the consensus on important issues rarely happens in the real world. Being so, the accommodation should be sought. When considering the changes that need to be made, it is helpful to consider whether changes are being made in structures, processes, or attitudes [4-7].

4.5 SSM in Practice

Since its creation in the 1970s, the SSM has been the most used methodology in the field of soft systems thinking. Several hundred documented examples report the successful use of SSM in ecology, the conclusion of public policies, business management, etc. The book Learning for Action [7] describes case studies in which SSM was used both in management situations and in the field of information systems. The way SSM is applied in case studies is different, except for the fact that they are strongly oriented to do something about the problematic situation [7].

Although the SSM is applied worldwide, most SSM applications are concentrated in the UK or countries that are under its influence, such as Australia, Canada and South Africa.

In Brazil, the use of methods based on soft systems approach in non-structured problem situations has been mild but constant and has provided up to now dozens of doctoral theses and master's dissertations involving institutions of the Federal Universities of Santa Catarina, Rio de Janeiro, Pernambuco and Minas Gerais (UFSC, UFRJ, UFPE and UFMG), the Aeronautics Institute of Technology at the Department of Aerospace Science and Technology (ITA/DCTA), the University of São Paulo's School of Economics, the Business Administration and Accounting School at Ribeirão Preto (FEA-RP/USP), and the Getulio Vargas Foundation (FGV-SP) [29]. About half of these theses were related to SSM. Studies involving SSM can also be found in more than one hundred publications in periodicals and events in Brazil.

5. SOFT SYSTEMS APPROACHES AND THE NUCLEAR AREA

An obvious limitation of conventional safety management methods lies in the fact that, in nuclear installations, technical (e.g. technology, tools, equipment), organizational (e.g. management system, organizational structure, governance, resources), human (e.g. knowledge, thoughts, decisions, actions) and external factors related to safety performance are constantly interacting, often producing unpredictable and undesirable results, which characterizes a non-structured problem situation. In this case, a problem manifested in one of

the factors may have its origin in another factor, making the isolated and non-integrated evaluation of these factors omit relevant information to the decision making process. This situation may have contributed to the accident at the Fukushima Daiichi nuclear power plant [1-2,30]. On the other hand, the systemic approach to safety addresses the whole system by considering the dynamic interactions within and among all these factors. In particular, soft systems methodology (SSM), with its characteristic of examining the problem situation from different perspectives would, see the interaction of the different factors in an integrated way and from different perspectives.

Despite this, the application of techniques, models or methodologies based on soft systems thinking in the nuclear industry has so far been inexpressive. Perhaps the only explicit application in the nuclear area is the application of SSM in the work developed by Ivan Salati de Almeida when executing a study aiming at improving the problem situation involving the Brazilian nuclear regulatory process [31]. In this work, it was considered the points of view of the applicant, licensee, licensor, public, non-governmental organizations, that raised situations perceived as problem situations and that after applying the SSM methodology resulted in proposals for improvement of the problem situation, which was "systematically desirable" and "culturally feasible".

However, some signs point to a possible change in this picture. Since 2012, therefore, shortly after the accident at the Fukushima Daiichi nuclear power plant, the IAEA started to host a series of technical meetings, training workshops, conferences and publications [32], highlighting the need for the traditional approach to safety should be complemented by a systemic approach that considers not only the human, organizational and technological factors that contribute to safety, but also the complexity of the interrelationships among them. [1,2,30].

In a recent workshop, also promoted by the IAEA in 2016 had as the main objective to develop, among the participants, a realistic understanding of the complexity inherent of nuclear safety. In this event, Stanley Deetz [30] pointed out that nuclear power plants, regulatory processes, political processes, and environmental events and the relations among them are more complex than mere the complicated systems, and suggested that approaches based on systems thinking should be considered in safety studies involving nuclear installations. Also in this event, Deetz presented the basic concepts of the systems approach highlighting its main currents, properties and methodologies. Soft Systems Methodology received special attention in this event, being the object of some practical exercises [30].

In fact, SSM takes into account individuals representative of the perspective of all stakeholders who can somehow contribute to a transformation of the problematic situation. When applied in nuclear safety management, depending on the case, SSM may consider not only the nuclear power plant, and its individuals and organization, but all other relevant stakeholders, such as operators, vendors, regulators, contractors, technical support organizations (TSOs), corporate organizations and international organizations. In addition, if necessary, individuals with expertise in the social and behavioural sciences may also be included in SSM. This diversity of point of views provided by the SSM will also allow that issues which can be regarded as known by a stakeholder (so-called known knowns) can help to elucidate another stakeholder on issues in which he is aware that he does not know about (so-called known unknowns) or on issues that are not aware of the fact that he does not know about them (so-called unknown unknowns). Depending on the situation, this could be carried

out for technical, organizational, human and external factors related to safety performance, allowing a truly holistic and structured view of the problem.

Supported by complemental methodologies and methods in a so-called methodological pluralism, SSM will be the key tool of a research project, led by this paper's authors, which main objective is the structuration and transformation of complex problems concerning the safety management of the IPEN/MB-01 research reactor located at the Nuclear and Energy Research Institute (IPEN-CNEN/SP), Brazil.

6. CONCLUSIONS

In this paper, emphasis was placed on the soft systems thinking, which focuses on the development of qualitative models based on interpretation and intersubjectivism that initially aim to structure problems involving complex social systems to later transform them. Soft systems thinking is inserted in the systemic approach, in which all stakeholders' point of views are considered, as well as their interactions throughout a given period of time. This feature is aligned with the recent IAEA efforts for the development and application of a systemic approach in safety management in order to promote a sustainable safety culture improvement in nuclear installations. Some of the methods that use the systemic soft approach are SSM, SODA and SCA, all of which have the potential to be used in nuclear safety management. For its methodological consistency and flexibility, Soft Systems Methodology (SSM) is one of the most promising methods for a short-term application concerning safety management of nuclear installations. Understanding the complexity of human, organization and technical factors, how they relate with one another and the complexity of the system as a whole is a key factor of the SSM that allows the decision-makers to make conscious decisions by putting problems in a more realistic context.

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