A Multi-domain Approach Toward Adaptations of Socio-technical Systems: The Dutch Railway Case-Part 1

1st Mohsen Jafari Songhori
*Department of Design, Production and Management**
University of Twente
Enschede, Netherlands
M.Jafarisonghori@utwente.nl

2nd Leo A.M. van Dongen*
University of Twente
Enschede, Netherlands
L.a.m.vandongen@utwente.nl

3rd Mohammad Rajabalinejad*
University of Twente
Enschede, Netherlands
M.rajabalinejad@utwente.nl

***Abstract*—Socio-technical systems are highly complex as they contain a number of domains each of which including numerous interdependent elements. With such complexity, policy makers and managers need to adapt (make incremental changes in) socio-technical systems, and currently available approaches for such adaptations are rare. Consequently, and to fill this gap, this paper takes a multi-domain approach based upon Design Structure and Multi-domain matrices to develop a multi-domain model of socio-technical system. Moreover, that model is analyzed according to both the change propagation measures of the non-human domain and the information processing view of the stakeholder domain of socio-technical systems. Application of this method for the Dutch railway system is discussed in Part 2 of this paper.**

***Index Terms*—Socio-technical systems, Multi-domain Matrix, Design Structure Matrix, Change Propagation, Information Processing View**

I. Introduction

Grounded in the general systems theory [47], socio-technical systems conceptualize systems as consisting of two independent, but linked, systems: a technical system and a social system [32]. The former is composed of equipment and processes, while the latter consists of people and relationships [27]. For instance, while an infrastructure is mainly a complex engineering system, but it is a socio-technical system: in addition to the fact that it contains many hardware/technical elements, it also involves people in different roles/positions [35].

In recent years the increasing availability of compututational tools has enabled gathering of (and analysing) data about the socio-technical systems. Similarly, in this paper, we present a multi-domain approach that aims to identify performance-enhancing adaptations in the domains of socio-technical systems. The core ideas of our approach relies on the four distinct notions. First, rather than planning a socio-technical system, identifying adaptation possibilities is recommended [3]. Second, socio-technical systems include several inter-related domains (e.g., stakeholders, functional, technical), and thus, a multi-domain approach [11] toward those systems appears to be plausible. Third, change lies at the heart of safety critical systems like power plants, and railway systems [16], and hence, change propagation measures can be used to examine the non-human (e.g., technical) elements of socio-technical systems. Fourth, those results obtained from analysing the non-human domain, and the information processing view of organizational systems [18] can be used to examine stakeholders coordination/communication structures.

The rest of this paper is organized as follows. The next section discusses the streams of relevant literature. Then, the method and its steps are presented in details. Finally, the discussion and conclusion sections end our paper.

II. Relevant Literatures

In this section, we present a short review of the streams of literature that examine (a) socio-technical systems, (b) design structure matrix, and (c) change propagation in technical systems. These three topics are selected as they constitute the core parts of both the context and the proposed method in this paper.

A. Socio-technical systems and Adaptation

Early attempts to study socio-technical systems are those by [44], [17]. They state that those systems can only be understood when social, psychological, environmental and technological systems are assessed as a whole. In streams of the relevant literature, different definitions have been provided for socio-technical systems. For instance, these systems are considered to “involve both complex physical-technical systems and networks of interdependent actors” [12]. As another field specific definitions can be the one discussed in the Information Systems (IS) field, where IS are contemplated as “ socio-technical systems involving the interplay of technology components (hardware and software), people (with cognitive capabilities and associated shortcomings), data (to capture real-life situations) and organizational issues (processes and management)” (page 284 in [20]).

In order to describe socio-technical systems (STS), scholars have examined the common attributes of those systems. In general, common features of STS include (1) large number of elements [8], (2) nonlinear interactions [19], [36], [39], [48],

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adaptive capacity [28], feedback loops [30], [29], and emergent properties [37].

Another relevant aspect is that since socio-technical systems are highly complex, a deliberate and comprehensive and outcome-oriented planning process may not be possible for such systems [3]. Moreover, situations in which deliberate design is possible and effective from those situations in which it may not be, should be distinguished (ibid). Thus, evolutionary models that allow for learning and adaptation can be an alternative for analysing/improving socio-technical systems. Such adaptive methods will be in line with the previously stated principle of socio-technical designs ("minimal critical specification of rules") that demands no more to be specified than what is absolutely essential in such systems [1].

B. Design Structure Matrix and Change Propagation

The Design Structure Matrix (DSM) is a popular visualization tool for system/processes modeling, especially for purposes of decomposition and integration [5]. A DSM displays the relationships between elements (e.g., technical, human, etc) of a system in a compact manner: A square matrix with identical row and column labels (that represent the elements of a system). Cells inside a DSM are either zero and one: presence of one (**zero**) indicates that the column element has (**no**) impact (or interaction) on the row element (see [5]). One of the main advantages of DSM models is their simplicity, as complex tools quickly become challenging to represent and understand [6].

The DSM tool can be used in various domains to model interactions within one particular domain (e.g., technical domain). For instance, a product (or technical) DSM illustrates its architecture which is "the arrangement of components interacting to perform specified functions" (page 302 in [7]). Another type of the DSM tools is the organizational (or stakeholders) DSM in which an organization consists of "organizational units" such as teams, departments, and individuals that connect to each other according to reporting/lateral/information flow relationships (ibid). Such organizational DSMs are considered as stakeholders matrix that shows the list and interactions of all human entities within a system. There are other DSM types, and as discussed in below, process/activity DSM and functional DSM can be developed and analysed for systems.

In addition to the domains themselves, their interactions or across domains should be modelled. The multi-domain matrix MDM is a matrix-based approach that relates/maps two DSMs of two different domains [11]. For instance, often, stakeholders/organizational units use/control/supervise technical/physical components. Thus, one MDM can be a **stakeholder×technical MDM matrix**. The list of possible DSM and MDM matrices is shown in Figure 1, and in below, we briefly describe each of those matrices.

During developing and designing a new product, often a change to one part of the product will bring changes to other parts [9]. More formally, *change propagation* is seen as the process by which a "change to one part or element of an existing system configuration or design results in one or more

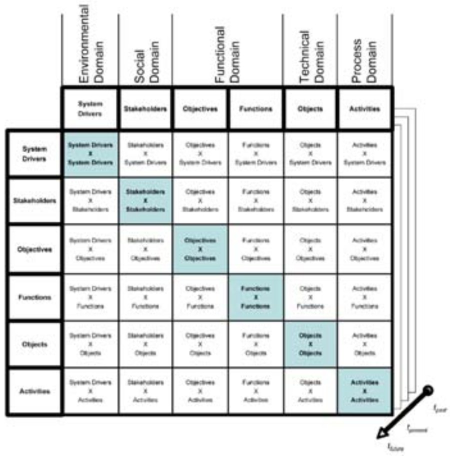

Fig. 1: Engineering Systems Multi-Domain Matrix, adopted from [2].

additional changes to the system, when those changes would not have otherwise been required" [15]. Having such process in engineering systems enables designers and managers to develop and operate those systems on schedule and within budget [21].

Change propagation research and literature relates to different fields (e.g., management, engineering design, product development, complexity), and have been growing in the last decades. The special issue on engineering change in the Journal of Research in Engineering Design [13] and a comprehensive overview paper [23] illustrate parts of that growth.

Two notions of the change propagation research need to be highlighted as our paper utilizes them. On the one hand, and from the perspective of change propagation, components of a product (technical system) fall into different categories [15], [21]: (1) constants that remain unaffected by change, (2) absorbers that absorb more changes than they cause, (3) carriers that absorb and cause a similar number of changes, and (4) multipliers that generate more changes than they absorb. On the other hand, scholars have developed different frameworks and methods for assessing and managing change propagation. For instance, taking DSM matrix into account, the change prediction method evaluates how changes spread through a product [9]. Relevantly, our paper uses a network approach toward measuring and evaluating change propagation within a non-human (technical) domain of a socio-technical system.

III. Multi-domain approach for identifying design strategies of socio-technical systems

We develop a multi-domain approach for categorizing elements of a socio-technical system, and identifying design strategies for them. This method proposes the following four steps:

1) **Define scope:** The first step is form an analysis team to conduct this methodology and also to define the scope of

an understudy socio-technical system. The analysis team conducts this methodology to identify design strategies for that socio-technical system. In this regard, the analysis team should consider two points. On the one hand, the system of interest and its boundaries should be clarified [22]. On the other hand, as explained in the next steps, the analysis team should make a model of the system. That is, the level of details or granularity to be incorporated in the model should be determined in a way that satisfies the essential and consequential trade-offs of a model (page 12 in [31]).

2) **Select and define critical domains:** The core notion of our approach toward socio-technical systems is to develop a simple and abstract view of those systems. In doing that, at first, the analysis team needs to identify and define the domains common to all socio-technical systems. Scholars of different fields view similar sets of common domains for socio-technical (and engineering) systems. As an example, and as shown in Figure 1, [2] defined five domains for engineering systems: (i) environmental [the exogenous components that influence or are affected by the system], (ii) social [the human elements and the relationships], (iii) functional [e.g., the goals and purposes of the system and its functional architecture], (iv) technical [physical, nonhuman components of the system], (v) process [processes and tasks performed within or by the system]. Other researchers define and suggest similar set of system domains (e.g., [49], [4], [25],[34]).

   After identifying the common domains of a system, the analysis team should choose the highly relevant domains. Such a decision of this team might be dependent on the availability of data.

3) **Collect data and build design structure and multi-domain matrices:** Once all desirable domains are identified, the analysis team should start collecting data via different methods (e.g., interviews, checking relevant sources, questionnaire). Next, as discussed in below, the team builds the relevant and required (according to the selected domains) instances of design structure and multi-domain matrices.

   As discussed earlier, depending on the selected domains, the responsible team needs to build and develop a number of relevant DSMs and MDMs. For example, if in analysing a socio-techncial system, its analysis team focuses only on organization and product/technical domains, then, they need to develop two DSMs (the product and organizational DSMs) and one MDM (stakeholder×technical matrix)[1]. However, for another socio-technical system, its analysis team may contemplate three domains, namely, organization, product, and goals. Such a team then should build three DSMs (the product, organizational, and goals DSMs) and three MDMs (stakeholder×technical, stakeholder×goals, and goals×technical matrices).

4) **Analyse multi-domain matrices:** As discussed earlier, from change propagation perspective, any non-human element of any engineering/socio-technical system can belong to one of the following types [15]: constants, carriers, multiplier, and absorber. Using DSMs and MDMs, and by conducting this step, the analysis team classifies all non-human (e.g., technical and physical) elements of its socio-technical system.

   At first, and using the non-human DSM (i.e., non-human domain), the analysis team creates a set S as collection of all non-human elements. For instance, if in analysing a socio-techncial system, the analysis team focuses only on the organization and product/technical domains, they develop only two DSMs (the product and organizational DSMs). Moreover, a set $S = \{i | i \in$ rows of product DSMs$\}$ is built by collection of all rows (or columns) of the product DSM.

   Using set S, the analysis team builds a network view $\mathcal{V}$ of the non-human DSM matrix. The edges of network $\mathcal{V}$ are developed according to the cells in the non-human DSM as follows. If that DSM is a symmetric matrix (e.g., the cell in column i and row j is the same as the cell in column j and row i), then, presence of a non-zero (non-blank) cell in the DSM matrix between any two elements makes an edge between the corresponding nodes; otherwise, there will be no edge between those nodes. Thus, for such a symmetric matrix, the resulting network $\mathcal{V}$ will be an undirected network. However, and contrarily, if either of the DSM matrix is asymmetric, then, the corresponding network $\mathcal{V}$ will be a direct network. Moreover, each edge $v_{ij} = 1$ has given a weight w_{ij} that shows the strenght of dependency among elements i and j.

   Since the method aims to capture both direct and indirect dependencies, the analysis team should define the spectrum of chains (i.e., number of steps) through which they think changes will propagate. Let denote this change propagation spectrum by β. As this decision can have significant effects on the results of analysis, the analysis team should follow a collective approach and based on a through undersntading decide about the spectrum of change propagation. A general rule can be that for a socio-technical system with $N = |S|$ total non-human elements, a change propagation spectrum taken in the following range can be advisable: $\beta \in [0.5N, N]$.

   Calculation of an estimation of the initial influential and susceptability measures is another task of the analysis team. The initial influence of an element i is defined as the weighted sum of all elements that are impacted by this element either directly or indirectly through a

[1] The shown MDM matrices in Figure 1 uses object to represent matrices and elements of the technical domain. Moreover, it differentiates between stakeholder×objects and objects×stakeholder matrices. In particular, the former represents interactions by which technical elements (or objects) act on an organizational element, and, the latter illustrates the interactions by which stakeholders act on a technical component (or an object). In this paper, for the sake of simplicity, we aggregate those two versions, and define only one matrix.

number of steps lower than β. In the equation in below, $\mathbb{O}_{i*}$ represents a network path from node i to any other node over network $\mathcal{V}$ that the size of the path is lower than β (or $|\mathbb{O}_{i*}| < \beta$). The equation also presumes that there are r' number of such network pathes.

$$\phi_i = \sum_{q=1}^{q=r'} \sum_{a,b} w_{ab} \times v_{ab} \qquad \exists \mathbb{O}_{iq}, |\mathbb{O}_{iq}| < \beta \quad a, b \in \mathbb{O}_{iq} \tag{1}$$

Similar the initial influential measure, the initial susceptability measure of an element i can be calculated as the weighted sum of all non-human elements that impact this element either directly or indirectly through a number of steps lower than β. In the equation in below, $\mathbb{O}_{*i}$ represents a network path from node i to any other node over network $\mathcal{V}$ that the size of the path is lower than β (or $|\mathbb{O}_{*i}| < \beta$). In addition, there could be r'' number of such network pathes.

$$\theta_i = \sum_{q=1}^{q=r''} \sum_{a,b} w_{ab} \times v_{ab} \qquad \exists \mathbb{O}_{qi}, |\mathbb{O}_{qi}| < \beta \quad a, b \in \mathbb{O}_{qi} \tag{2}$$

The aforementioned initial measures are utilized to create the influential and susceptability measures. This is done in line with the following logic: A component becomes more influential (susceptable) if it impacts (influenced by) the other components that themselves are affecting (impacted by) a higher number of (or with more intensity) the components. Therefore, the following equations define the influential (Φ_i) and susceptability (Θ_i) measures of a non-human element:

$$\Phi_i = \sum_a \phi_a \qquad \forall a, v_{ai} = 1 \quad \text{or} \quad v_{ia} = 1; \tag{3}$$

or there is an edge

$$\Theta_i = \sum_a \theta_a \qquad \forall a, v_{ai} = 1 \quad \text{or} \quad v_{ia} = 1; \tag{4}$$

or there is an edge

After calculating the measures in equations 3 and 4, the analysis team can use them to identify those non-human elements that are either (i) *constant* with relatievly low values of influence and susceptability (low values of Φ_i and Θ_i); (ii) *absorbers* with high susceptability and low influence values; (iii) *carrier* with high values of influence and susceptability; or (iv) *multipliers* with high value of influence and low value of susceptability.

In the organization and management literature, it has been argued that "the greater the task uncertainty, the greater the amount of information that must be processed among decision makers during task execution in order to achieve a given level of performance" (page 28 in [18]). Similarly, we argue that in a socio-technical system, those non-human elements that are classified as different classes, according to change propagation behavior, impose different information processing requirements on the overall performance system and its stakeholders. In particular, in decreasing order of information processing requirements, the non-human elements classes are: (i) carriers, (ii) multipliers/absorbers, and (iii) constants. We denote the information processing requirements of a non-human element i by parameter R_i. This parameter could be defined as a categorical variable, and the analysis team could decide about its levels; for instance it may take values as follows:

$$R_i = \begin{cases} 0.1, & \text{i is classified as constant} \\ 0.5, & \text{i is classified as multipliers/absorbers} \\ 1, & \text{i is classified as carriers} \end{cases} \tag{5}$$

As the next step, the analysis team should calculate the overall information processing requirements of each stakeholder as follows. By contemplating the stakeholders DSM, they elaborate a set of stakeholders $SH = \{h | h \in \text{rows of organizational DSM}\}$. Then, using the MDM matrix of dependencies between organizational and non-human domains, they determine the participation level of each stakeholder h in funtional/operational processes of non-human element i (denoted by P_{ih}). As an example, three levels of such particpations could be low, medium, and high, which are respectively presented by $P_{ih} \in \{0, 0.5, 1\}$. Lastly, by using participation levels and identified classes of non-human elements, the analysis team can calculate the overall information processing requirements of each stakeholder h as:

$$I_h^{Re} = \sum_{i \in S} P_{ih} \times R_i \tag{6}$$

With respect to uncertainty, different organizational structures and mechanisms that provide varying information processing capaciy for decision-makers/managers can be used to cope with the information processing requirements imposed by internal and external sources of uncertainty. Some of those organizational structures in decreasing order of information processing capacity are: (1) group meetings, (2) direct contact, (3) planning, (4) special reports, (5) organizational rules and regulations. (page 561 in [10]).

The information processing view of organizations expects higher performances when there is a match between information processing requirements of an organization and information processing capacity of its structure [45]. Thus, pursuing this logic, the analysis team can order the stakeholders based on their the overall information processing requirements (I_h^{Re}), and according to that order, then design/recommend coordination/integration mechanisms. That is, the analysis team follows the following rules:

- Rule I: Group meeting and direct contact are advisable for communications/interactions of the human elements who have the highest overall information processing requirements.
- Rule II: Whereas, those stakeholders who have the lower overall information processing requirements should be more prioritized for communications by special reports and organizational regulations.

Besides the aforementioned rules for adapting the stakeholders communication structure, the analysis team can apply the following rules for adaptation of the non-human elements interactions:

- Rule III: Elements that are categorized as constant components are neither influenced by nor impact the other elements. Thus, those elements can be seen as suitable candidates for non-human related design improvements (e.g., re-designing a technical subsystems).
- Rule IV: From the perspective of change propagation, carriers can be seen as the riskiest set of elements, and consequently, they deserve resource allocation prioritization in terms of system architecture and interfaces.

IV. Discussion and Conclusion

Socio-technical systems are highly complex, and as discussed earlier, it is recommended to take adaptive approach toward managing them [3]. In this paper, we presented a multi-domain approach that aims to identify performance-enhancing adaptations in domains of socio-technical systems. At first, using DSM and MDM matrices, our model builds a multi-domain perspective of socio-technical systems. In particular, both of the stakeholders and non-human domain matrices are developed.

In the next step, and for the non-human (technical) domain, four categories of the elements that require different adaptation strategies are identified based upon the change propagation perspective. This aspect is highly related to many socio-technical systems, as change lies at the heart of safety critical systems like power plants, railway systems [16]. Relevantly, a network-view based model of inter-dependencies among the non-human elements is developed, and then, overall influence and susceptability scores of each element are calculated. Using those scores, and with regard to the change propagation aspect, the method classifies the non-human elements into four classes: constants, absorbers, multipliers, and carriers. Each of these categories imply different change propagation behaviours, and hence, managerial actions. For instance, carriers are risky components that need more resource, whereas, constants are less risky and can be redesigned/adapted more easily.

For the stakeholders domain, we take an information processing view of an organizational system which expects such systems' information processing requirements to be matched with their information processing capabilities [18]. Similarly, we argue that in a socio-technical system, those non-human elements that are classified according to change propagation behavior impose different information processing requirements on the overall performance system and its stakeholders. Thus, our method calculates the overall information processing requirements of each stakeholder. To that end, the results of non-human domain analysis (or categories of the non-human elements) are utilized, and therefore, change propagation features are assumed to cause different levels of information processing requirements for the involved stakeholders. Consequently, by aggregation, and ordering the overall information processing requirements of stakeholders, they are ordered in order to identify those with highest/lowest overall information processing requirements.

According to the information processing view of organizations, different organizational/coordination mechanisms (e.g., group meeting, reporting procedures) provide different levels of information processing capability. For instance, it is argued that as uncertainty increases, organizations use pre-established plans/schedules for cordination than other coordination mechanisms like group meeting and direct contacts [46]. With these highlights, then, our method recommends to adapt coordination among stakeholders such that those stakeholders with high (low) overall information processing requirements coomunicate/coordinate their decisions/actions based on the coordination mechanisms that provide high (low) information processing capabilities.

The presented method in this paper opens up at least two directions for future research. First, while it is formulated as a generic approach that focuses on domains of a socio-technical system, application of this method on the industrial cases could reveal potentials/shortcomings of this method. Therefore, Part 2 of this paper illustrates utilizing our method for the Dutch railway system. Second, although this paper aims to identify performance-enhancing adaptations in socio-technical systems, its approach could still be further enhance by explicitly taking into account other rules/principles. As an example, ethical rules in data/information domains could be an alternative analysis to be included in the future extended version of the presented method.

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