A Multi-domain Approach Toward Adaptations of Socio-technical Systems: The Dutch Railway Case-Part 2

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***Abstract*—Socio-technical systems are highly complex in which a number of domains each of which including numerous interdependent elements are present. Therefore, for adaptation of socio-technical systems, Part 1 of this paper presented a multi-domain approach based upon Design Structure and Multi-domain matrices to develop/analyze a multi-domain model of those system. Moreover, that model is analyzed according to both (1) the change propagation measures of the non-human domain and (2) the information processing view of the stakeholder domain of the socio-technical system. This papers presents application of the presented method in the Dutch railway system. We have reviewed the relevant railway literature, and interviewed with a number of the Dutch railway experts and validated our model. The results are presented in this paper.**

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

I. Introduction

Socio-technical systems conceptualize systems as consisting of two independent, but linked, systems: a technical system and a social system [14]. The former is composed of equipment and processes, while the latter consists of people and relationships [10]. 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 [3], (2) nonlinear interactions [8], [15], [17], [19], adaptive capacity [11], feedback loops [13], [12], and emergent properties [16]. 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 [1]. Thus, evolutionary models that allow for learning and adaptation can be an alternative for analysing/improving socio-technical systems.

Part 1 of this paper presents 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: (1) rather than planning a socio-technical system, identifying adaptation possibilities is recommended [1], (2) socio-technical systems encompass several inter-related domains (e.g., stakeholders, functional, technical), and thus, a multi-domain approach could be an appropriate approach toward those systems [4], (3) change lies at the heart of safety critical systems like power plants, and railway systems [6], and hence, change propagation measures can be used to examine the non-human (e.g., technical) elements of socio-technical systems, finally, (4) those results obtained from analysing the non-human domain, and the information processing view of organizational systems [7] can be used to examine stakeholders coordination/communication structures.

More specifically, Part 1 uses the Design Structure Matrix (DSM) and multi-domain matrix (MDM) notions [2], [4] to analyze socio-technical systems through the following steps:

1) **Define scope**
2) **Select and define critical domains**
3) **Collect data and build design structure and multi-domain matrices**
4) **Analyse multi-domain matrices**

The rest of this paper is organized as follows. The next section discusses the application of our method for the Dutch railway system. Lastly, the discussion and conclusion sections end our paper.

II. Practical Case: The Dutch railway system

A. *Define Scope and Select Critical Domains*

In order to define system boundary and select its critical domains, the initial steps of the process of developing DSMs and MDMs of the Dutch railway system include a review of the relevant references.

Through that review process, we have found a couple of useful models. Among those, two Master theses done in the Engineering Systems division at Massachusetts Institute of Technology [9], [5] investigated high-speed rail (HSR) systems. In particular, [5] conceptualize HSR systems being composed of many heterogeneous subsystems which are controlled and maintained by human & non-human (e.g., automated procedures). They also presented the technical DSM of HSR

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system which is comprised of the following six interacting physical subsystems (page 31 in ibid): (1) rolling stock, (2) power supply, (3) signaling, (4) track, (5) station, and (6) control center.

Once we finished the aforementioned review process, we defined our system boundary to include all railway development, railway operations and maintenance related domains. Morevoer, technical and stakeholders/organizational domains appeared to be critical for the Dutch railway system.

B. Build Design Structure and Multi-domain Matrices

We have a reliable knowledge about the Dutch railway system as the second author of this paper has had the CTO position at NS, the Dutch railway operator firm, for more than 15 years. Thus, we have taken the formerly discussed technical DSM with six subsystems and expanded it as follows. Each of the six technical subsystems is decomposed into more detail level, and this generates lower level subsubsystems, or elements. For instance, the next seven elements can be seen as those that form rolling stock: (1.1) wheelset+Bogie, (1.2) traction equipment, (1.3) body shell, (1.4) air-conditioning, (1.5) control, (1.6) braking, and (1.7) utilities. By this process, we have identified a list of 36 technical elements of the Dutch railway system that are shown in Table I in below.

In the next step, and in order to identify all relevant interactions among the technical elements, we have identified a set of functions that each technical element is supposed to provide. The set of functions is either related to either flow of energy/information/material or other specific functionalities. As an example, consider *Traction Equipment* as one element of the rolling stock subsystem. Thinking of the functionalities that this element provides, one could list items like (1) having rotational energy flow, (2) moving rolling the stock over track, (3) changing speed of train, (4) stablizing the rolling stock.

Having the functions of each element identified, by the following procedure, we recognized the interdependencies among the technical elements. For each pair of elements i_1 and i_2, we examined their corresponding functions, and if we found those functions related, then, the pair of elements are considered interdependent. Example of such interdependency can be consideration of *Wheelset+Bogie* and *Traction Equipment*. From Table I, one can find that both of these elements are related to the function of *"moving rolling stock"*. Another case of interdependency is for *control subsystem* and *air conditioning subsystem*. These two elements both have a common functionality of *"control temperature"*. Consequently, these two elements are interrelated, too.

Once all interdependent elements are identified, they are evaluated regarding their strength, and some are considered as strong while others as weak. The former and latter are depicted by "1" and "0.5" in a technical DSM which is illustrated in Figure 1. An example of weak interdependency is the impact of the elements of control center subsystem on the elements of station (e.g., parking areas, information display): although to some extent, the latter depends on the former, the latter can perform its main functionalities even without the former.

We have also developed stakeholder/organizational DSM (Figure 2). During the development process of this DSM, the generic safety control structure of the high-speed rail (HSR) systems, presented by (page 90 in [9] and page 178 in [5]) was one of the useful sources. According to this framework, two critical inter-related layers operate within a railway system: system development which is comprised of R&D/design/manufacturing, and train system operations is comprised of train operation and maintenance. These activities are regulated by regulatory institutions which are located at the highest level of the model.

In this elaborated DSM, we have rolling stock and infrastructure managers with roles in: (i) managing operations, (ii) managing maintenance, and finally, (iii) managing the entire physical system integration. Furthermore, passengers and train operator/dispatcher are included. Flows of information/feedback are parts of this DSM, too. For instance, the rolling stock manager sends requirements for the rolling stock maintenance manager, and the latter, instead, shares maintenance reports with the former. As another example, the same rolling stock manager provides the passenger with the train schedules/plans/route guidelines, etc.

Besides the within domain interactions, we have also identified across domain interactions by elaborating technical×stakeholder MDM. This MDM matrix relates stakeholders and technical components (see Table 2). A reader is likely to find this matrix more easy to understand as it indicates which stakeholder (and to what extent) acts/decides/uses which of the technical subsystems. For example, an infrastructure maintenance manager often makes maintenance-related decisions, and thus, this stakeholder impacts the signaling and track subsystems. The shown number inside parenthesis indicates the level of interrelationships (i.e., "2" and "1" stand for high and low levels, respectively). Likewise, the infrasturcture manager influences those two subsystems through making operations-related decisions. And, also this manager is impacted by becoming informed about the situations of the two subsystems.

In the shown technical×stakeholder matrix, a reader may find some interaction less clear. For instance, for interaction between passenger (stakeholder) and station (technical), we use the following fact that passenger can affect traffic flow at a station, and also a station can impact the quality or service satisfaction of passengers (e.g., around 45% of Dutch rail passengers cycle to the station- page 50 in [18]). In addition, one row and one column in Table 2 represent the overall information processing requirements of stakeholders and technical elements that are discussed in below.

TABLE I: The Dutch railway system: Technical subsystems, elements, and their functions

Subsystem	Element	Functions
	1.1 Wheelset+Bogie	*Move rolling stock over track*
	1.2 Traction equipment	*Rotational energy flow; Move/carrries rolling stock over truck; Change speed trains; stablizes rolling stock*
	1.3 Body shell	*Drink, disposals, passenger flow; Trasfer thermal flow; Isolate passengers from external environment; Locate/hold passengers*
	1.4 Air conditioning	*Generate thermal energy; Trasfer thermal flow; Control temperature*
1. Rolling stock (RS)	1.5 Control	*Signal control; Control cabine temperature/speed/passenger flow*
	1.6 Braking	*Change speed;*
	1.7 Utilities	*Dispose human and other wastes; Supply passengers with foods/drinks*
	2.1 Light signals with ATB/ETCS	*Status of track, speed limit; Permission to drive train; Indicate speed limits; braking actions*
	2.2 Local signals by train personnel	*As functions of 2.1*
	2.3 Single signaling-ERTMS1	*As functions of 2.1*
2. Signaling system (SS)	2.4 Single signaling-ERTMS2	*As functions of 2.1*
	2.5 Dual signaling-ERTMS1	*As functions of 2.1*
	2.6 Dual signaling-ERTMS2	*As functions of 2.1*
	3.1 PlatCreates	*Passenger flow; Transfer passengers; Separate passengers into services; Connect train cabine and station; Create entrance passengers;*
	3.2 Walls and buildings	*Passenger flow; Transfer passengers; Separate passengers into services; Provide resting areas for passengers/drivers/conducters*
	3.3 Bikes and Parking areas	*Passenger flow; Join passenger trip to door to door services*
	3.4 Customer InCreateation displays/CCTV cameras	*Signal status of railway services; Announce situations of railway services; Detect station mal/functionality*
3. Station (ST)	3.5 Ticketing and Passenger service offices	*Separate passengers into services; Join passenger trip to door to door serivces; Prepare pasengers for trips; Announce situations of railway services; Detect station mal/functionality*
	3.6 Shops and resturants	*Prepare passengers for trips; Supply passengers with foods; Provide resting areas for passengers*
	4.1 Single-track	*Position rolling stock; Allow smooth movement of rolling stocks; keep rolling stock*
4. Track (TR)	4.2 Double-track	*Position rolling stock; Allow smooth movement of rolling stock; keep rolling stock*
	4.3 Multi-track	*Position rolling stock; Make passenger/rolling stock flow; Allow smooth movement of rolling stock; keep rolling stock*
	5.1 Bridges	*Make passenger/rolling stock flow; keep rolling stock*
	5.2 Viaducts	*Make passenger/rolling stock flow; keep rolling stock*
	5.3 Tunnels	*Make passenger/rolling stock flow; keep rolling stock*
	5.4 Embakements	*Allow smooth movement of rolling stocks; Adjust level of tracks*
	5.5 Service (maintenance) yard	*Keep rolling stocks/tracks for maintenance*
5. Route/Structure (RAS)	5.6 Workshop (modernization)	*Keep rolling stocks/tracks for modernization*
	5.7 Depo (maintenance facilities)	*Adjust technical features of rolling stock/tracks; Detect technical perCreateance/issues of rolling stock/tracks*
	6.1 Transmission line	*Electrical/magnetic flow*
	6.2 Traction substation	*Electrical flow; Convert/ electrical energy*
6. Power supply (PW)	6.3 AutotransCreateer	*control the voltage of trasmission lines; TransCreate voltage*
	6.4 Overhead contact line	*Electrical flow; Supply electrical power*
	7.1 ATC-EG	*Speed signals; control deceleration; Control speed*
7. Control center (CC)	7.2 ERTMS-ATC	*Speed signals; control deceleration; Control speed*
	7.3 Other control systems	*control deceleration; Control speed*

TABLE II: Technical*stakeholders MDM of Dutch railway under hypothetical arrangement and the overall information processing requirements (see Table 3).

Technical										Overall Information Requirement (see Table 3)
Rolling stock	maintenance decisions (2)		operations decisions (2)		decisions (2)		traffic flow (2)		traffic flow (2)	3,6
Signaling system		maintenance decisions (2)		operations decisions (2)		decisions (1)		traffic flow (1,5)		5
Station					decisions (2)		traffic flow (0.5)		traffic flow (1)	1
Track	decisions (1)	maintenance decisions (2)		operations decisions (2)		decisions (1)				3
Route and structures		decisions (2)		decisions (2)	decisions (1)					4,6
Power supply					decisions (2)	decisions (1)				0,8
Control center	scheduling (1)		scheduling(2)				updates (1)	updates (1)		1,1
Stakeholders	Rolling stock maintenance manager	Infrastructure maintenance manager	Rolling stock operations manager	Infrastructure operations manager	Rolling stock asset manager	Infrastructure asset manager	Train driver	Train conductor	Passenger	
Overall information processing requirement see in equation (6)	11,3	25,2	9,4	25,2	15,4	8,8	8,8	8,6	8,2	

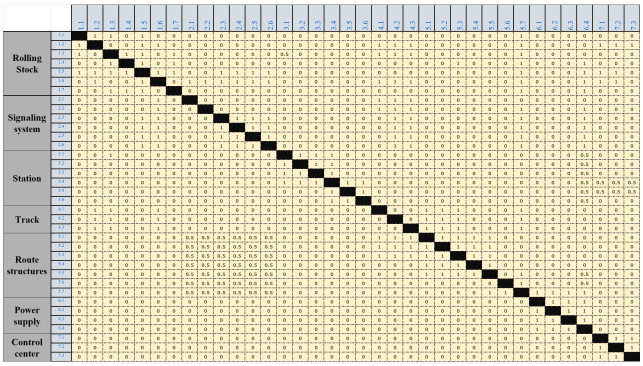
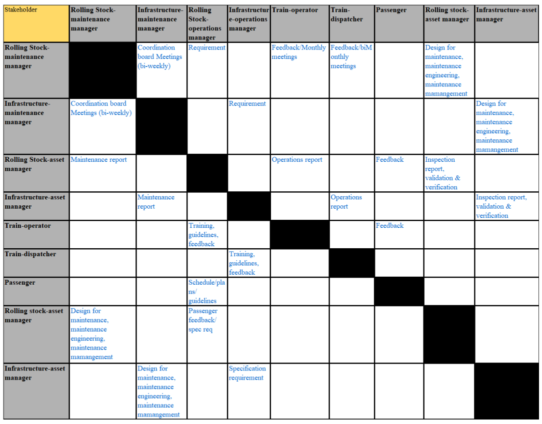


Fig. 1: Technical DSM of the Dutch railway system. The technical elements are illustrated using their IDs provided in Table 1.



Stakeholder	Rolling Stock-maintenance manager	Infrastructure-maintenance manager	Rolling Stock-operations manager	Infrastructure-operations manager	Train-operator	Train-dispatcher	Passenger	Rolling stock-asset manager	Infrastructure-asset manager
Rolling Stock-maintenance manager		Coordination board Meetings (bi-weekly)	Requirement		Feedback/Monthly meetings	Feedback/biMonthly meetings		Design for maintenance, maintenance engineering, maintenance mamangement	
Infrastructure-maintenance manager	Coordination board Meetings (bi-weekly)			Requirement					Design for maintenance, maintenance engineering, maintenance mamangement
Rolling Stock-asset manager	Maintenance report				Operations report		Feedback	Inspection report, validation & verification	
Infrastructure-asset manager		Maintenance report				Operations report			Inspection report, validation & verification
Train-operator			Training, guidelines, feedback				Feedback		
Train-dispatcher				Training, guidelines, feedback					
Passenger			Schedule/plans/ guidelines						
Rolling stock-asset manager	Design for maintenance, maintenance engineering, maintenance mamangement		Passenger feedback/ spec req						
Infrastructure-asset manager		Design for maintenance, maintenance engineering, maintenance mamangement		Specification requirement					

Fig. 2: Organizational DSM of Dutch railway system.

C. Analyze Multi-domain Matrices

Applying the analysis step discussed in Part 1 of this paper on the DSM and MDM matrices enabled us to understand and identify possible design strategies for the Dutch railway system. Initially, we chose a value for the change propagation spectrum, $\beta = 4$. Then, based upon their influence and susceptability scores, we classified the technical elements, see Figure 3 and Table III.

The resulted categorization of the technical elements provides some insights. First, for some subsystems, the elements of each subsystem seem to occupy one particular quadrant of the plot in Figure 3. That is, the elements of each subsystem (highlighted by the same color) mainly belong to one of the four classes. For exmple, the elements of *signaling system* and *track* tend to have high influence and susceptability, and thus, they are carriers. However, the elements of *station* and *power supply* have both low influence and susceptability, and they form the category of constants.

Second, for some other subsystems of which the elements belong to more than one category, they spread over small area in Figure 3. Thus, their elements belong to mainly two categories. Consider the *rolling stock* subsystem. Its elements are mainly either absorber or multiplier. In other words,

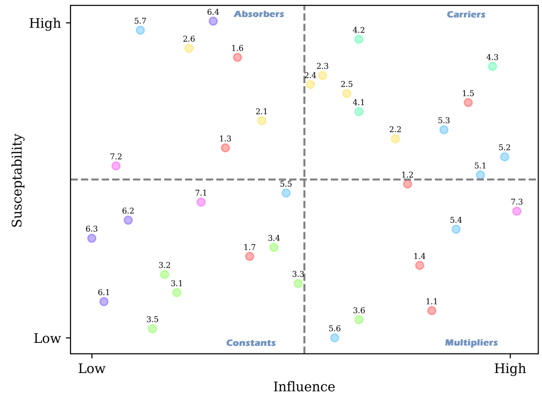


Fig. 3: Classification of the Dutch railway technical elements using $\beta = 4$; The technical elements are illustrated using their IDs provided in Table 1.

TABLE III: The technical elements of the Dutch railway system: Influence, susceptability, and overall information requirements using $\beta = 4$.

Element	Influence	Influence Rank	Susceptability	Susceptability Rank	Sum Info Requirements	Subsystem
1.1	0,32	28	0,03	3	3,6	RS
1.2	0,31	26	0,12	17		
1.3	0,14	11	0,19	21		
1.4	0,32	27	0,05	8		
1.5	0,39	31	0,25	26		
1.6	0,14	12	0,37	31		
1.7	0,14	13	0,06	9		
2.1	0,16	14	0,20	24	5	SS
2.2	0,26	25	0,20	22		
2.3	0,23	19	0,34	29		
2.4	0,22	18	0,33	28		
2.5	0,24	21	0,32	27		
2.6	0,10	8	0,42	32		
3.1	0,07	7	0,04	5	1	ST
3.2	0,05	6	0,05	7		
3.3	0,20	17	0,05	6		
3.4	0,18	15	0,07	10		
3.5	0,04	5	0,01	1		
3.6	0,25	22	0,02	2		
4.1	0,25	22	0,21	25	3	TR
4.2	0,25	22	0,43	33		
4.3	0,43	33	0,34	30		
5.1	0,43	32	0,15	18	4,6	RAS
5.2	0,44	34	0,16	20		
5.3	0,32	29	0,20	23		
5.4	0,36	30	0,07	12		
5.5	0,20	16	0,12	16		
5.6	0,23	20	0,01	0		
5.7	0,02	4	0,77	34		
6.1	0,02	1	0,03	4	0,8	PW
6.2	0,02	3	0,08	13		
6.3	0,01	0	0,07	11		
6.4	0,10	10	1,00	35		
7.1	0,10	9	0,11	15	1,1	CC
7.2	0,02	2	0,16	19		
7.3	1,00	35	0,09	14		

those elements have a high value for either influence or susceptability score, and not for both. This argument becomes more clear by focusing on those score themsleves (shown in Table 3) rather than on the ranks (which are used for the plot in Figure 3). By looking at both Tables I and III, one could find that the elements with the folowing IDs have higher than the average influence score (which is 0.22) and a low value for the susceptability score: 1.1, 1.2, 1.4, and 1.5. Whereas, the element 1.6 has higher than the average susceptability score (which is 0.2) and a low value for the influence score.

Similar arguments can be made for the other similar subsystems whose elements tend to belong to more than one particular categories. For instance, the elements of the *route/structure* subsystem are members of either the sets of multiplier or carriers. Again, those elements (except the element 5.7) mainly have a high influence and a low susceptability scores.

In the next step, by using the classification of the technical elements, the overall information processing requirements (hereafter, OIPR) of each subsystem is calculated. These calculations are provided in Table 2. First, the OIPR levels of the elements of each subsystem (depending on the classification those elements and based on equation 5 of Part 1 of this paper) are aggregated into an OIPR level for that particular susbsystem. Second, taking the participation levels of stakeholders in Table II, we calculate the overall imposed information processing requirements on each stakeholder (see equation 6 of Part 1 of this paper).

The OIPR of stakeholders indicates which stakeholders should have more priority with regard to adapting their organizational structures. According to the rules I and II discussed in Part 1 of this paper, the coordination and communications among stakeholders with a high level of OIPR need to be in forms of either group meetings or direct contacts. Conversely, the same rules recommend reporting and organizational regulations for coordination/integration among those stakeholders with a low level of OIPR.

Overall, the following adaptation strategies on stakeholders coordination/communication can be formulated (see Figure 2):

- Establishing group meetings/direct contacts should be possibly incorporated for adapting communications of the following stakeholders: (1) infrastructure maintenance manager, (2) infrastructure operations manager, and (3) rolling stock operations manager.
- Reporting and organizational regulations are advisable for coordination among the following stakeholders: (1) infrastructure asset manager, (2) train driver, and (3) train conductor.

Besides the rules I and II with organizational focus, the other rules in Part 1 recommend a couple of adaptations toward technical elements and interfaces. Those latter rules along with the plot in Figure 3 imply two messages:

- Technical changes in the elements/interfaces of station and power supply subsystems seem to be less likely to bring change propagations within the Dutch railway system.
- Technical changes in the elements/interfaces of signaling system and track subsystems can propagate, and therefore, if those two subsystems are being adapted/changed, they deserve to recieve more resources compared to the other subsystems (that are going through a change process).

III. Discussion and Conclusion

Socio-technical systems are highly complex, and adaptive approach toward managing them are advised [1]. In this paper, we presented an application of the presented multi-domain approach in Part 1 of our paper. It illustrates potentials of that method (see Part 1) in identifying performance-enhancing adaptations in domains of the Dutch railway system as a socio-technical system.

At first, using DSM and MDM matrices, we build a multi-domain perspective of the Dutch railway. 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. That is done based upon the change propagation perspective [6]. For the stakeholders domain, and according to the information processing view of an organizations, we argue that in a socio-technical system, those non-human elements that are classified in different classes according to change propagation, impose various information processing requirements on the overall performance system and its stakeholders.

We have applied our method to a highly complex socio-technical system: the Dutch railway system. Our analysis indicates that some stakeholders like infrastructure maintenance and rolling stock operations managers should have more of group meetings for their communications/coordinations, whereas, the other stakeholders like train driver and train conductors might incorporate less information capability mechanisms (e.g., reporting) for their coordinations. In addition to these, our technical domain analysis implies that changes in the subsystems like station and power supply are less likely to propagate, and conversely, the opposite is the case for some other subsystems (e.g., signaling and track).

The presented practical case in this part (Part 2) of our paper opens up some directions for studying the other socio-technical systems. For instance, different sytems of either the healthcare or the aviation industry could be analyzed in a similar approach.

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