Analysis of interdependencies of the Mexico City Metro System

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Abstract: The Mexico City Metro underground system has been regarded as the second largest Metro in North America after the New York City Metro. It is believed that in 2006 the system served over one billion passengers, the fifth highest in the world. Given this, a threat to the Metro transport system may either have an impact on other industries that rely on it or to the other modes of transportation in the City. Interdependencies amongst the key components of the Metro system, therefore, must be understood and adequately addressed. The paper addresses the modelling of the interdependencies amongst the Metro lines by applying a 'Systemic Safety Management System' (SSMS) model. The paper gives an account of the ongoing research project.

Keywords: Interdependency, Metro System, Mexico City, SSMS Model.

1. INTRODUCTION

1.1. Critical infrastructures & Its Context

The concepts and the importance of "interdependencies" and "critical infrastructures" took interest after the publication of the report "Critical Foundations: Protecting America's Infrastructures", the report of the U.S. President's Commission on Critical Infrastructure Protection (PCCIP) [1]. The PCCIP has defined an "infrastructure" as a network of independent, mostly privately-owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services [1]. Moreover, the Commission focused on eight critical infrastructures; i.e., telecommunications, electric power systems, natural gas and oil, banking and finance, transportation, water supply systems, government services, and emergency services. More recently, the Critical Infrastructure Assurance Office (CIAO), an interagency office created under Presidential Decision Directive (PDD) 63 to assist in coordinating the federal government's initiatives on critical infrastructure protection. The CIAO defined infrastructure as "the framework of interdependent networks and systems comprising identifiable industries, institutions (including people and procedures), and distribution capabilities that provide a reliable flow of products and services essential to the defence and economic security of the United States, the smooth functioning of governments at all levels, and society as a whole". Moreover, the CIAO's report included the following critical infrastructures: food/agriculture (production, storage, and distribution), space, numerous commodities (iron and steel, aluminium, finished goods, etc.), the health care industry, and the educational system [2].

A number of studies have been conducted on interdependent critical infrastructures. For example, the International Risk Governance Council (IRGC) has conducted research on both the risks associated with five individual infrastructures and the risk associated with the increasing interdependency between them. The infrastructures considered by the IRGC were {1} electric power and gas supply; {2} information and communication services -as provided by the internet as well as ICT to monitor and control other infrastructures; {3}urban water supply and waste water treatment; {4} rail transport. [3,4].

Rinaldi et al. [5] has proposed four classes of interdependencies; i.e.: 'physical', 'cyber', 'geographic', and 'logic'. 'Physical' interdependency occurs when two infrastructures are physical interdependent if the state of each is dependent on the material output(s) of the other. An infrastructure has a 'cyber'-

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interdependency if its state depends on information transmitted through the information transmitted. 'Geographic' interdependency, on the other hand, occurs when infrastructures are geographically interdependent; i.e., if a local environmental event can create state changes in all of them. Finally, 'logical' interdependencies occurs when infrastructures are logically interdependent if the state of each depends on the state of the other via a mechanism that is not physical, cyber, or geographical connection. A number of research has been conducted on the survivability and vulnerability of infrastructure systems [6-17].

1.2. Examples of Critical Infrastructures

Any disruption or destruction of key technical systems could have significant consequences; for example, significant impact on public health and safety, public confidence, negative impacts to the environment, the economy. Many of these systems house significant amounts of hazardous materials, fuels, and chemical catalysts that enable important production and processing functions. A brief description of some of the following systems is presented in the subsequent section: water, telecommunications, energy, and transport.

1.2.1 Energy

Energy may be regarded as one of the key infrastructures in the modern society. The energy sector is commonly divided into two segments in the context of critical infrastructure protection: electricity and oil and natural gas [5]. It is believed the electric industry services almost 130 million households and institutions. The United States, for example, consumed nearly 3.6 trillion kilowatt hours in 2001. Moreover, every form of productive activity (e.g. businesses, manufacturing plants, schools, hospitals, or homes) requires electricity. [1,5].

1.2.2 Water

Any Nation's water sector is critical from both a public health and an economic standpoint. The water sector consists of two basic, yet vital, components: fresh water supply and wastewater collection and treatment. Sector infrastructures are diverse, complex, and distributed, ranging from systems that serve a few customers to those that serve millions. These utilities depend on reservoirs, dams, wells, and aquifers, as well as treatment facilities, pumping stations, aqueducts, and transmission pipelines. [1,5].

1.2.3 Telecommunications

The telecommunications sector provides voice and data service to public and private users through a complex and diverse public-network infrastructure encompassing the Public Switched Telecommunications Network (PSTN), the Internet, and private enterprise networks. The PSTN provides switched circuits for telephone, data, and leased point-to-point services. Because the government and critical infrastructure industries rely heavily on the public telecommunications infrastructure for vital communications services, the sector's protection initiatives are particularly important. [1,5].

1.2.4 Transport

The transportation sector consists of several key modes: aviation, maritime, rail, road and public mass transit. As a whole, the various transportation modes provide mobility of the population and contribute to the quality of life of any country's inhabitants. Given the above, a threat to the transportation sector may either have an impact on other industries that rely on it or to the other modes of transportation. Interdependencies amongst modes of transportation, therefore, must be adequately addressed. [1,5].

2. THE MEXICO CITY METRO SYSTEM

The Mexico City Metro underground system has been regarded as the second largest Metro in North America after the New York City Metro. It is believed that in 2006 the system served over one billion passengers, the fifth highest in the world. The Metro system map showing the eleven lines is shown in Fig1; the Metro system comprises a total of 175 stations and 106 underground stations. Every Metro line transports hundreds of thousands of users every single day. [18].

Figure 1: The Mexico City Metro system. [18].

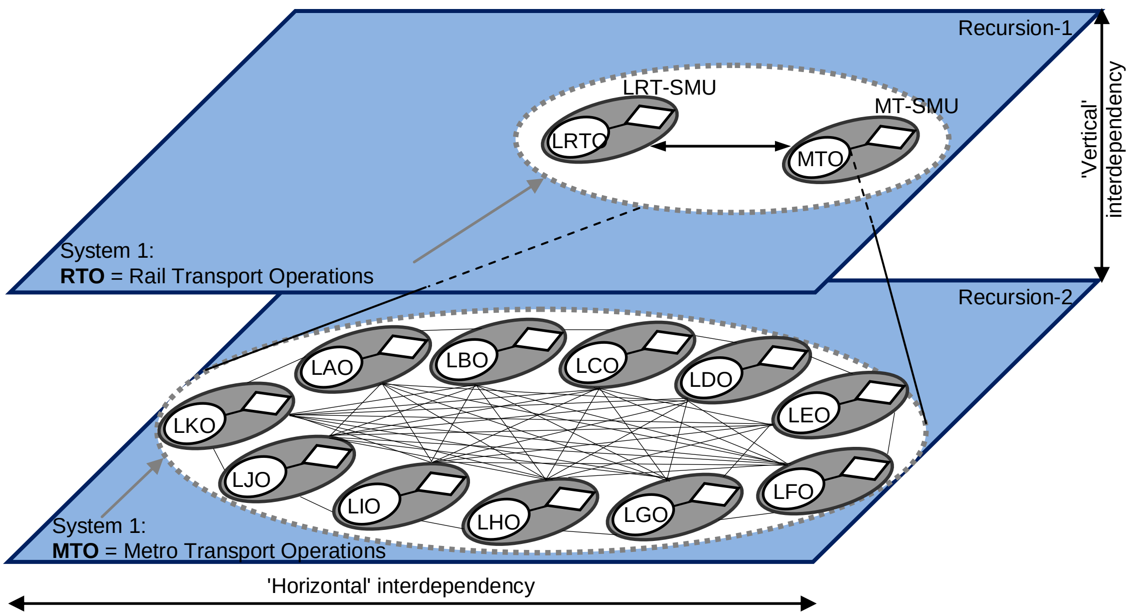
As mentioned in the introduction section, any disruption in any component of a highly interrelated system may cause a 'domino' or cascading effect. For example, on 22nd January 2008, a failure in the power supply system to the Metro system caused a disruption and affected several lines within the system; the incident caused trains to halt in 68 stations and it is believed the incident affected about

83,000 users. Also, the public transport could not cope with the amount of users being affected by the disruption. [19].

3. A SSMS MODEL

A 'SSMS' model is intended to maintain risk within an acceptable range in any organization's operations. The model is proposed as a structure for an effective safety management system. It may be argued that if all the sub-systems and connections are present and working effectively, the probability of a failure should be less than otherwise. A brief description of the 'structural organization' of the model is given as follows: this systemic approach to safety management consists of a set of five necessary and sufficient interrelated subsystems, labelled as systems 1 to 5. *System 1, safety policy implementation*, consists of various operations of an organization in which the organization's safety policy must be implemented. *System 2, safety co-ordination*, ensures that the various operations of system 1 operate in agreement. *System 3, safety functional*, ensures that system 1 implements the organization's safety policies. *System 3*, safety audit*, is part of system 3 and it is concerned with safety sporadic audit. System 4, safety development, is responsible for identifying strengths, weaknesses, threats, and opportunities that can suggest systemic changes to the organization's safety policies. *System 4*, confidential report*, is part of system 4 and it is concerned with confidential reports or causes of concern that may require direct and immediate intervention of the corporate management. Finally, *system 5, safety policy*, is responsible for establishing safety policies for the whole organization. A full description of the model is given elsewhere [20-22].

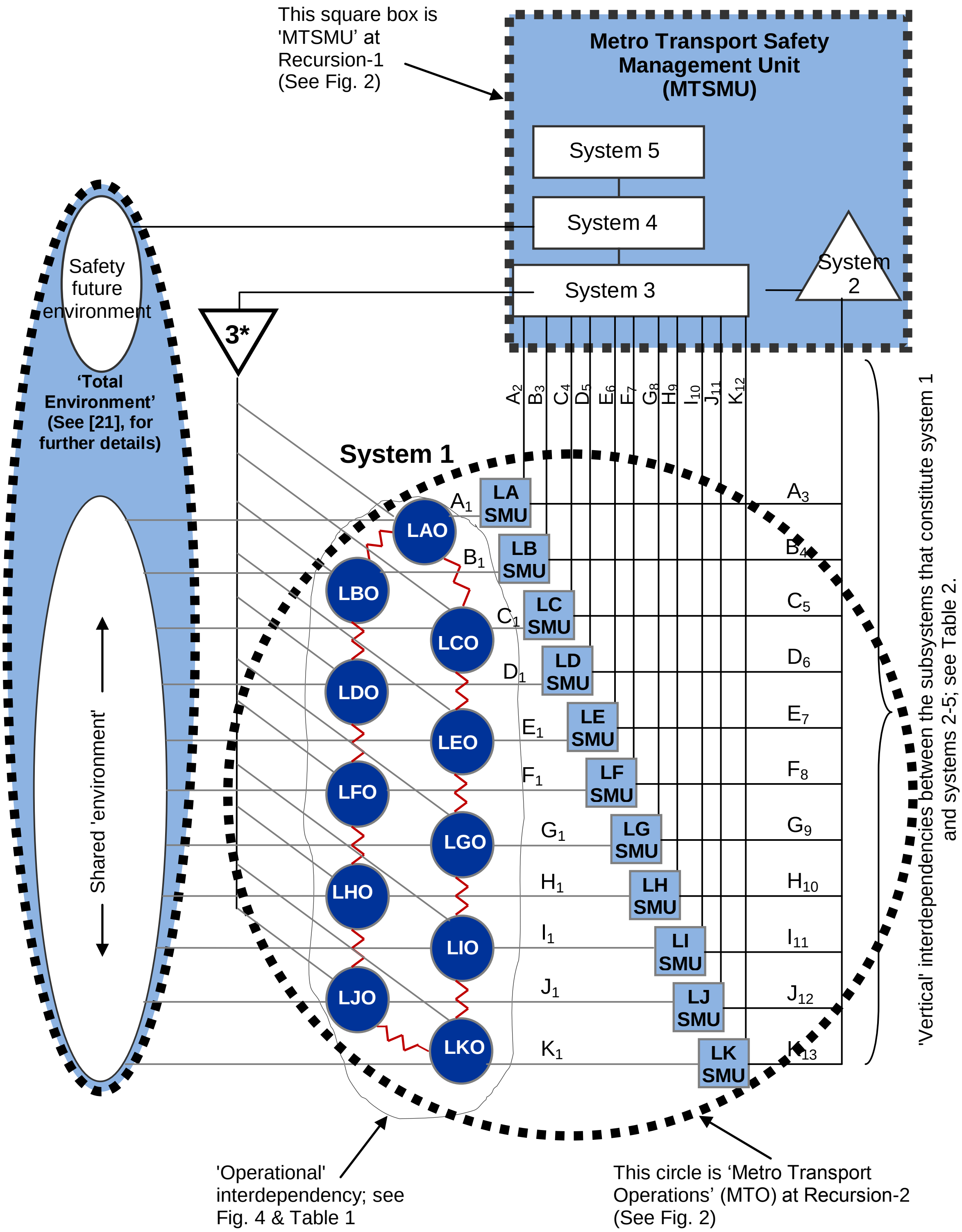
Figure 1: Recursive structure of a 'SSMS' model. (© Santos-Reyes).



Acronyms:

MT-SMU=Metro Transport-Safety Management Unit;
MTO= Metro Transport Operations
L_{A-K}-SMU= Line A-K Safety Management Unit;
L_{A-K}O= Line A-K Operations

Figure 3: 'Horizontal' & 'vertical' interdependency. (© Santos-Reyes).



Note: see Fig. 2 for details of the acronyms used in the figure.

Figure 4: 'Operational' interdependency. (© Santos-Reyes).

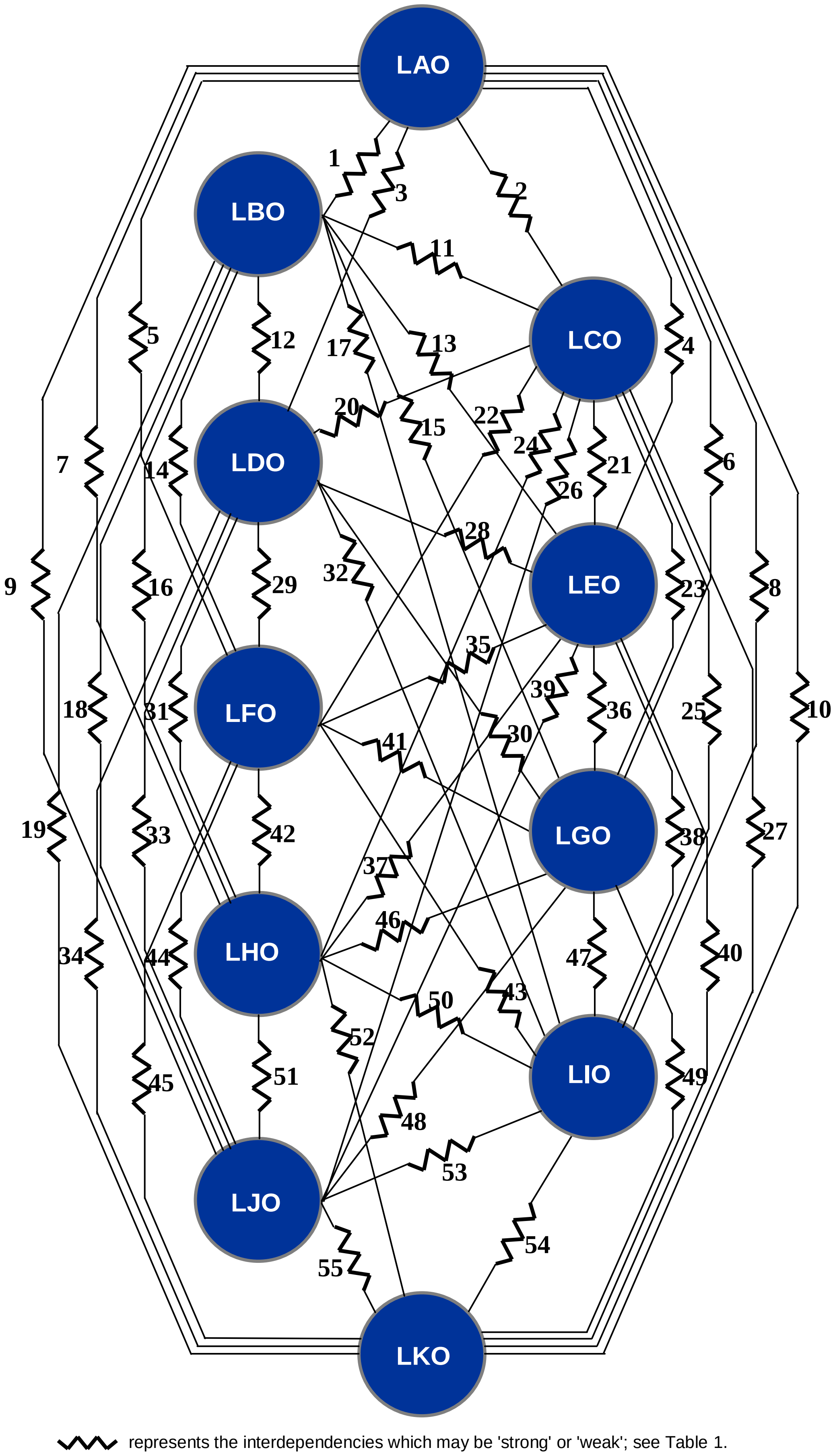


Table 1: 'Operational' interdependency amongst the Metro Lines.

	LAO	LBO	LCO	LDO	LEO	LFO	LGO	LHO	LIO	LJO	LKO
	Number of Zigzag lines shown in Fig. 4										
	S/W	S/W	S/W	S/W	S/W	S/W	S/W	S/W	S/W	S/W	S/W
LAO		1	2	3	4	5	6	7	8	9	10
			S	S	W	W	S	S	W	S	S
LBO	1		11	12	13	14	15	16	17	18	19
	S		S	W	W	W	S	S	S	W	W
LCO	2	11		20	21	22	23	24	25	26	27
	S	S		W	S	S	W	W	S	W	S
LDO	3	12	20		28	29	30	31	32	33	34
	S	W	W		S	S	W	S	S	W	S
LEO	4	13	21	28		35	36	37	38	39	40
	S	S	S	S		S	W	W	S	S	S
LFO	5	14	22	29	35		41	42	43	44	45
	W	W	S	S	S		S	W	W	W	W
LGO	6	15	23	30	36	41		46	47	48	49
	S	S	W	W	W	S		W	S	W	W
LHO	7	16	24	31	37	42	46		50	51	52
	S	S	W	S	W	W	W		S	W	S
LIO	8	17	25	32	38	43	47	50		53	54
	S	S	S	S	S	W	S	S		S	W
LJO	9	18	26	33	39	44	48	51	53		55
	W	W	W	W	W	W	W	W	W		W
LKO	10	19	27	34	40	45	49	52	54	55	
	S	S	S	S	S	W	W	S	W	W	

S='Strong' interdependency.
W='Weak' interdependency.

Table 2: 'Vertical' interdependency between System1 & Systems 2-3.

	LA-SMU	LB-SMU	LC-SMU	LD-SMU	LE-SMU	LF-SMU	LG-SMU	LH-SMU	LI-SMU	LJ-SMU	LK-SMU
	No. Channel Communication & Control connecting Systems 2&3 (Fig. 3)										
	ToI	ToI	ToI	ToI	ToI	ToI	ToI	ToI	ToI	ToI	ToI
System 2	A_3	B_4	C_5	D_6	E_7	F_8	G_9	H_{10}	I_{11}	J_{12}	K_{13}
	C & L	C & L	C & L	C & L	C & L	C & L	C & L	C & L	C & L	C & L	C & L
System 3	A_2	B_3	C_4	D_5	E_6	F_7	G_8	H_9	I_{10}	J_{11}	K_{12}
	C & L	C & L	C & L	C & L	C & L	C & L	C & L	C & L	C & L	C & L	C & L

ToI=Type of Interdependency.
C= 'Cyber' (e.g. shared information related to the Metro train position within the Line).
L= 'Logic' (e.g. decisions being taken yb the controllers).

4. MODELLLING INTERDEPENDECY FOR THE CASE STUDY

4.1. The Modelling Process

In order to model interdependencies, an 'infrastructure' has been considered as a 'system'; i.e., any entity which consists of interdependent 'parts'. Given this, two levels of recursion for the present case study are shown in Fig. 2. It can be seen that System 1 at level 1 contains the sub-system of interest; *i.e.,* 'Metro Transport Operations' and its associated Safety Management Unit (SMU); i.e., 'Metro Transport Safety Management Unit' ('MT-SMU').

Increasing the level of resolution of the system of interest, *i.e.*, 'MTO' at one level below recursion 1 will result in a system that contains the eleven lines that constitute the whole Metro system (i.e., system 1), at the level of recursion 2. The 'systems' identified in Fig. 2 have been represented in the format of the 'structural organization' of the model; i.e. systems 1-5 and their associated connections as shown in Fig. 3.

The following types of interdependencies have been identified in Fig. 3: {a} 'operational' ('circles'), see Table 1; {b} 'managerial' ('square boxes'); and {c} 'environmental' ('elliptical' symbol; these are not discussed here). These interdependencies occur 'horizontally' at one level of recursion only; i.e. at recursion 2.

'Vertical' interdependencies have been identified that they occur only between levels of recursions; in this particular case, between Systems 2-5 and system 1 (i.e. the eleven lines of the Metro system), as shown in Figs. 3, 4 & Table 2.

4.2. Summary of the Type of Interdependency Highlighted by the Model

4.2.1 'Vertical' interdependency

The principle of *recursion* has been proved to be a powerful concept in identifying 'vertical' and 'horizontal' interdependency. ('Recursion' may be understood as a 'system' contains and it is contained by another 'system'). 'Vertical' interdependency occur between two levels of recursions; 'horizontal' interdependencies, on the other hand, occur at every level of recursion (see Figs. 2-4). The identified systems were mapped onto the format of the 'structural organization' (i.e. systems 1-5) of the model (Fig. 3). The connections between every 'SMU' ('square boxes') with Systems 2&3 indicate the 'vertical' interdependencies; the nature of the relationship is managerial; see Table 2.

4.2.2 'Horizontal' interdependency

'Horizontal' interdependency amongst the collection of subsystems that constitute System 1 occur at every level of recursion. Three types of interdependencies have been identified: 'operational', 'managerial', and 'environmental'.

'Operational' interdependencies

'Operational' interdependency (circles) could be 'strong' or 'weak' (Fig. 4). A 'strong' interdependency implies that the operations are highly interdependent; for example, the 'correspondence' stations between two Metro lines has been considered here as a 'strong' interdependency. A 'weak' interdependency, implies a relatively 'weak' dependency; for example, the Metro lines with no 'correspondence' between lines were considered within this category. The results are shown in Fig. 3 & Table 1.

'Managerial' interdependency

The safety management units ('the square boxes') stands for the operations ('circle') that the management unit is supposed to regulate: the operations are 'under its control' (see the connections between every SMU and the operation shown in Fig. 3). However, when a disturbance occur in any of the SMU's operations, this in turn will propagate to the whole system. In order to bring the disturbance under control the communication amongst the SMUs becomes essential to achieve this. This is not shown here.

'Environmental' interdependency

The 'environment' is multi-dimensional; i.e. economical drivers; it contains of a market, of a supply-situation, of customers of users, of the general public, natural hazards. (See Figures 4&7). In general, the 'environmental' factors are those that threaten the 'system'; for example, the cascading effects caused by the earthquake and tsunami of March 11, 2011 in Japan. [23]. This is not shown here.

5. CONCLUSION

The paper has presented a 'systemic' approach to model interdependencies for the case of Mexico City Metro system; i.e., by applying a 'SSMS' model. It has been found that interdependencies occur 'vertically and 'horizontally'. 'Vertical' interdependencies occur between two levels of recursions. 'Horizontal' interdependencies occur at every level of recursion; i.e.: {a} 'operational'; {b} 'managerial; and {c}'environmental'.

More research is being conducted on: a) identifying interdependency amongst the SMUs (Fig. 3); b) identifying the 'environmental' interdependency (Fig. 3); c) Identifying the interdependency between 'operations' (circle) and their associated 'management units' (square boxes) as shown in Fig. 3; and d) modelling the 'emergency response' in the context of the 'SSMS' model in case of an emergency situation such as the example described briefly in section 2.

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