Conceptual Analysis and Modeling of a Metro System

A. Spiteri Staines

***Abstract*—** This work considers the problems associated with different levels of complexity and decomposition for modeling a large transport system such as an underground metro. Such a system shares many parallelisms with many complex computer systems. Many techniques based on object oriented analysis and decomposition can be found. The problem is formulated and the France Paris metro system is considered. Different considerations related to decomposition, functionality and system representation have to be considered for this autonomous system. For a solution three main levels or views are used. These are i) top, ii) middle and iii) low level view. The solutions are based on the three main levels, hierarchy, modularization, decomposition and certain assumptions. The implementation is explained and discussed.

***Keywords*—**Modeling, Object oriented analysis and design, System engineering, Transport.

I. Introduction

SYSTEM modeling has evolved from a simple process to embrace complex issues. One of the main goals of system modeling, synonymous with object orient analysis, serves to complete and improve the design of the final artifact. Usually a greater emphasis is placed on the design rather than the analysis of systems. Models can present an abstracted version of the system. This helps to reason about the main underlying properties.

Analysis is explicitly concerned with the user's world, the problem, its application domain and the system's essential responsibilities. The design of the solution is dependent on the outcome and precise analysis of the problem. Analysis is concerned with studying and observing a problem domain. A specification is created using external observed behavior. From this it should be able to document and create information that explains the functional and quantifiable operational characteristics of a system. Issues like reliability, availability, performance, service levels, etc. all need to be included. These can be derived from proper models developed during the analysis stage.

Three basic types of models can be considered. These are: i) Physical, ii) Mental and iii) Symbolic. Physical models include diminutive and imitation behavior of the real thing. They can represent very well the actual system. Symbolic models can take the forms of schematic diagrams, block diagrams including other notations like flowcharts, graph models, UML notations, formal methods, etc. Symbolic models can be visual or non visual.

Symbolic modeling techniques are suited for treating and representing complex distributed systems like networks. Hence for modeling a metro system symbolic modeling offers significant advantages like i) graphical or visual representation, ii) decomposition and scalability, iii) different viewpoints, iv) verifiability and verification of different parts, v) explicit communication with different stakeholders. Symbolic modeling can be used to define criteria and test certain hypothesis.

Classification of the system into different categories is important for understanding the complexities involved at the different levels.

A network is composed of locations, distribution, connections and resources. All these entities interact with one another and comprehending the interactions is important. Many systems in the external world can be conceptualized into a network. This is one of the main reasons why block notations, graph theory, Petri nets and higher order nets are recommended.

II. Background

One of the main tasks of systems engineering is the creation of representational structures for existing systems and new ones. Modeling a transport system or a traffic system such as an underground metro or a complex train system is a comprehensive and difficult task. Most of these systems employ diverse computer technologies and software control. A system, like an underground metro organization is a collection of trains, rails and station service points that exist at different levels. The servicing points serve as inlets and outlets for the flow of commuters. An underground metro is a highly organized transportation network. This necessarily places a high demand for parallel and temporal constraints. These are identified in as explained in [1],[2],[4],[6],[7][13].

Mainstream modeling approaches, such as those used for traffic, computer network, and communication systems tend to focus on i) theoretical solutions, ii) employ a single method for analyzing the problem and iii) support a limited number of views. It has been shown elsewhere that more than one technique or view should be associated with representing complex systems as in [2],[6],[13],[16].

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Anthony (Tony) Spiteri Staines, is with the Department of Information Systems, Faculty of ICT, University of Malta, (corresponding phone: 00356-21373402,e-mail: toni_staines@yahoo.com)

Previous work shows how Petri nets, higher order nets, Colored Petri Nets (CPNs) and similar constructs are useful; for describing networked systems involving parallel processes [3],[9],[8],[13]-[15]. This implies that they are also useful for modeling a metro or train network. However, different views and dimensions are involved in a complex metro system. For depicting such a network a single view is not sufficient. The ideas presented are not limited to modeling only this type of system. They can also be used for any type of system that is networked [4]-[8].

A metro system is considered to be a special transport system which requires operations like incidence management, flow control, precise time constraints and timings, etc. It is difficult to model all its aspects because of the parameters involved and even concepts, like changing behavior with time. Models used are a simplification of what is actually taking place. Complex conditions are ignored for the sake of modeling.

III. Problem Definition

This work deals with comprehending the issues for modeling a complex metro system. Unlike normal systems, a metro has a number of different views that require reconciliation. A transport system like a metro consists of several sub levels that are dependent on several variables and parameters that can indicate non-determinism. The complexity of the system has a direct effect on the monitoring of the system.

Any descriptive model is actually a simplification of how the real system works. Other problems are found in describing or representing the system. The issues related to the decomposition imply that different ways of representation need to be found. There are problems as to what is to be represented and how many levels should be included to describe the system.

By definition a metro is a real time system that has both hard and soft deadline characteristics. This type of system has to offer a high level as relates to the temporal quality-of-service (qos) guarantees. Obviously the more levels that are included the more complex the solution, so a tradeoff has to be sought. The concept of systems hierarchy can be used to offer a practical solution. An important aspect of a metro, is that normally the requirements would not change. This type of network is a permanent network. It is not a dynamic network that changes after some time elapses. Even if the configuration changes this is just a minor modification but the same pattern is repeated. If lines or routes are changed this would be just a simple case of reassignment. A solution should reflect these issues.

Some approaches might claim that for a well specified problem there is a single correct design solution. This reasoning can imply that other solutions are suboptimal. However normally this is not possible. It is evident from all the modeling techniques and concepts that are heavily used in systems analysis and design in conjunction with one another, that a single solution seldomly exists and still there are many different ways to formulate the same problem. Using a single way to represent a system implies the narrowing down of knowledge. The structures used to represent can become a limitation because they impose a restricted view. When considering large systems there are so many issues that different methods and techniques have much to offer.

A. Paris Metro System

The Paris-Metro system has been chosen to represent the problem domain. The reasons are that this networked system can provide an elaborate scenario for different types of decomposition, analysis and modeling that is not so straightforward.

In principle this metro is similar to other large metro systems like the underground system in central London and other places around the world. This metro is characterized by its large size, density, complexity and distribution.

A short description of the Paris Metro is that it represents an important symbol for the Paris city in France. It consists of elaborate architectural and complex engineering artifacts. Normally there are 14 distribution lines and also bus and other services. The main lines used exist at different levels. The line identification is facilitated by maps having different color codes for easy identification. The metro traffic is quite dense, but cyclical predictable behavior is the norm. Lines are bi-directional and have clear names and identities. There is a large overlap of metro stops at certain main stations and sub-stations. This is visible from a detailed metro map. Virtually almost all of central Paris is covered by stops which sometimes are within walking distance from each other. Trips allow travelers to swiftly access one direction to another in a given time frame of 60 seconds to a maximum of 2 minutes.

Lines share parallel operations interacting with one another at common places and from a temporal perspective. In a particular sense the metro exhibits multiple behavior. Obviously there must be several ways how to represent this.

B. Views, Decomposition and Functional Issues

From a computational perspective this system clearly fits the analogy of parallelism and distributed architectures. The size of the model reflects the computational complexity of the particular problem. The concept of breaking down the entire system into small components or entities facilitates verification and validation that can be carried out incrementally or sequentially. Reduction serves to simplify the process [8].

The idea of having separate views is based on the principle of complexity reduction. Having separate views, enables the proper understanding of parts of the system. Here, basically three main views or levels are considered. These are: i) architectural, top view or macro view. ii) middle view and iii) micro view. See fig. 1. The system can be studied in detail using the micro views. However just these views or studying the low-level behavior does not allow for the comprehension of the system as a unified whole. This is the reasoning for including the three views. Using reduced views can be considered to be a reductionist approach, which can be useful for comprehending the micro level. Using three or more views implies that different levels of granularity can be included in the model.

Top level: The system is considered as a complete artifact and the lower level details are ignored. However this level is not suitable for modeling and experimentation but rather for general representation.

Middle view: This is easier to comprehend by stakeholders. However again there are some difficulties and limitations as to use it for certain aspects of modeling. The middle view is meoscopic and consists of the interrelationships. This is not complete as at the low level and some details are definitely omitted. It could be suitable for modeling if it is combined with lower views.

Micro view: The micro views, microscopic or low level views, offer high fidelity. In these views the physical system operations can be considered in detail by isolating a system, such as a particular line from another. If the microscopic view for the Paris system metro is considered then the lines 1..14 are seen in detail. This implies that each line can be examined in isolation from each other.

Different levels or views can be combined with each other. The lines can be combined with each other at the stations or stops for particular requirements. This is like combining the meoscopic view with the microscopic view. In the system graph layout this implies adding a further layer of decomposition with micro and middle view combined.

As an analogy the individual lines are comparable to different computer programs or systems e.g. P1, P2, P3,…,Pn which are composed of deterministic metro stops, but it is possible to have non-deterministic linking between the metro stops at a given point in time. I.e. the link or switch from one line to another is non-deterministic.

The lines or trains are similar to multiprocessors sharing the same memory locations. This fits in with concurrency, parallelism and distribution of work. The metro has all the characteristics of a distributed system composed of subsystems and having various timing constraints. The metro can be considered to be a special type of network model.

C. Abstraction and Modeling Issues

The reasoning behind creating abstract models is to create simple understandable structures without many unnecessary details [2],[6]. It is not always simple to strike a balance. Ideally the elements in the model should map or represent elements in the real world system. The complex connectivity in a metro system implies that there are many nodes and edges in representational structures that are interrelated. The size of the system implies that conventional modeling techniques might result in descriptions that are too complex thus making it unfeasible.

IV. Problem Solution

Formulating and proposing a solution for modeling a metro system can be quite complex. There are various steps and representational factors that are important. Given the complexity of a dense metro system certain issues and criteria have to be met. For the solution, approaches common to system and software engineering have been considered. The architectural view can be separated from the functional view. This is done through decomposition.

These relate to classification of the system, its modularization via decomposition, etc.

The proposed solution is to use a three tier functional decomposition approach. This has been previously used for classifying transport systems like traffic modeling. The classification is briefly outlined in 2.2. Block diagram notations describe the macro view, middle view and the micro view.

A. Classifying the System as Autonomous

Here modularity refers to the autonomy of the system parts. Autonomous behavior is evident in the different lines. This means that each line is managed independently from another line. Each line is self regulating because its actual behavior is independent from other lines. At a deeper level autonomous behavior implies self healing and self control [10],[11]. Autonomous behavior results in new research challenges and opportunities.

From a modeling perspective, the metro has a number of autonomous parts. This means that correct models have to be generated for these parts. Specific modularity and abstraction are the key to developing autonomous system components. In terms of software programming and system design autonomous computing involves ideas like transparency of the design, using open ways for system representation [10].

If the system is represented using some form of graphs, then each specific node in the graph has its own authority and responsibility for different activities as indicated in fig. 3-4.

B. System Modularization through Decomposition

Modularization is a well known principle in both system and software engineering approaches [12]. For problem solving techniques, such as divide and conquer are well known and used to breakdown a big problem into smaller counterparts that can be solved individually. The principle of modularity is based on this. As software and system complexity increases modularity is very important.

Normally, in classical programming problems and system analysis modularity is used for identifying different main parts, after decomposition. In object oriented approaches modularity is a good way for abstracting problems. In the metro system, different concepts, synonymous with object oriented abstraction, are observable. These are object oriented like structures based on inheritance, abstraction, coupling and message pass through. The object oriented concepts are applicable to different levels of the system. Generalization along with class specialization are useful for explaining the system structure along with cohesion. See figure 1.

For a metro system, modularity can be used to understand better the system when models are to be developed. A metro system is composed of many components and parts at different levels of complexity. A good solution should employ principles of modularity in the analysis and design of the real system.

The concepts of modularity are directly related to structural hierarchy. A large network can be decomposed into smaller modules or subnets.

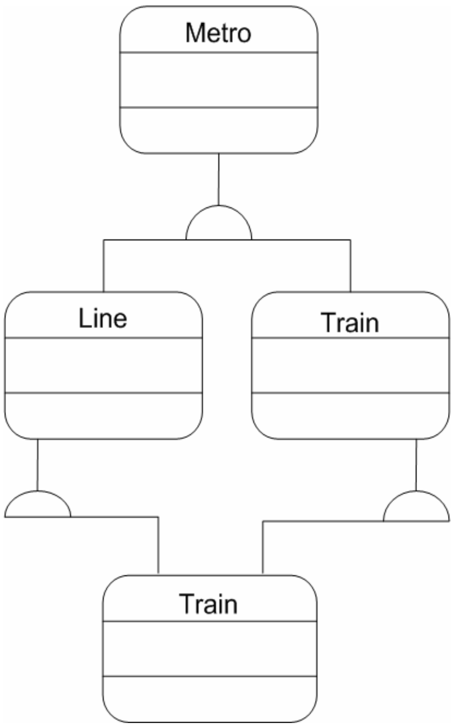

Fig. 1 metro class system hierarchy and multiple inheritance

C. Structural Hierarchy

Another way of decomposing and expressing component based systems is through using structural hierarchy and abstracting it. Structural hierarchy or abstraction hierarchy is useful for providing and explaining the structure of a particular system architecture in terms of its elements. The concept of structural hierarchy is well known and the idea is to be able to describe a system in terms of its components. Graph structures are particularly well suited to representing this hierarchy. Normally nested elements in the system are ignored or omitted from the graphical representation. See figure 2.

A metro system follows this hierarchy almost naturally. I.e. decomposition and different levels are easily noticeable. The three levels described previously are based on structural hierarchy. The use of structural hierarchy is commonplace when describing complex autonomous systems.

System graphs are suitable for depicting hierarchy in systems. A graph model for representing the metro system would be useful in this respect.

The metro structural hierarchy graph can be considered to be a dependency graph. From the graph different linear ordered sub paths can be generated. These sub paths describe how the system is configured and can be devoted to individual attention.

Each actual low-level or micro-level individual metro transport network is a linear ordered path that can be viewed in two directions. The metro stations are considered to be nodes or vertices and the distance between one station and the other are the edges. This can be represented as a digraph having cycles.

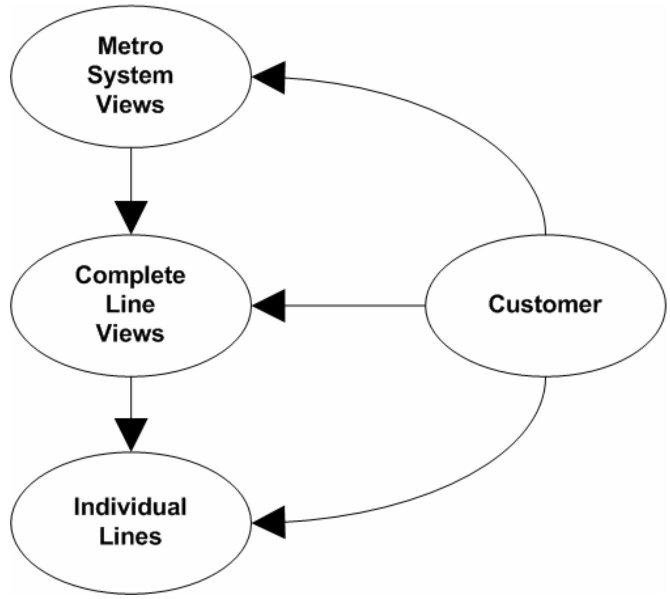

Fig. 2 view relationship graph

D. Metro System Decomposed Views or Levels

The following views or levels have been considered in the metro system. These are based on the principles of top down decomposition and hierarchy which are congruent with autonomous system engineering principles. See fig. 5.

The levels are: i) Macro view. This is also known as the macroscopic or low fidelity view in transport modeling. ii) Middle view. This is known as meoscopic or medium fidelity view. iii) Micro view. This is known as a microscopic or high fidelity view where more detailed physical behavior and interaction can be modeled. A hybrid view of the three can be created. This would depict the complete system.

The i) Macro view has a top level network and restricted system description outlining the system. ii) Middle view. More detail is shown with parts of the network and lines, possibly interaction. Structured diagrams, system graphs, network diagrams, colored network diagrams or charts can be used. iii) Micro View. More detailed system graphs showing cyclical or acyclical behavior are valid. State transition diagram or state charts, Petri nets and higher order nets, etc. can express the required detail. The micro can be a true representation of what is actually happening. However the micro view has to be considered in conjunction with the other views to make sense.

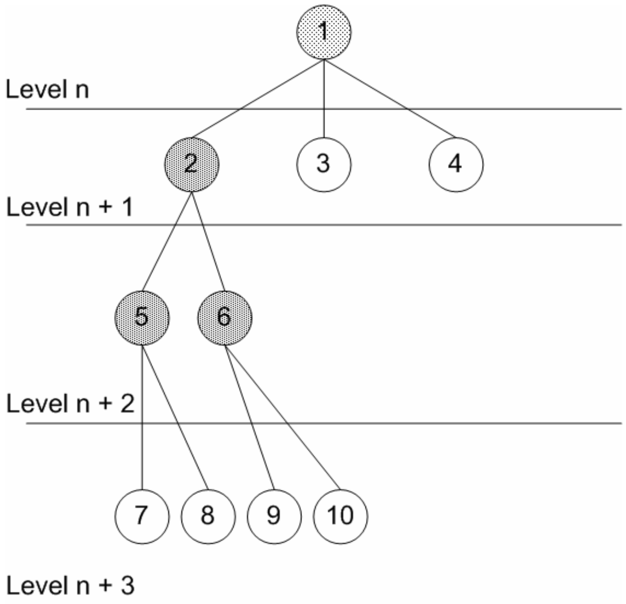

Fig. 3 system component hierarchy with autonomous components

E. Model Discovery

Model discovery refers to the process of comprehending a system and its components to the extent that it is possible to derive and discover new models.

The task of model discovery is not straightforward because it is dependent on what is going to be represented and at which level of abstraction.

For considering the metro system, the different levels or views considered like human interaction, task management, data management, system domain, etc. can be used to generate different models.

Here the generic system domain view is emphasized. In a real sense this view would require reconciliation with other views for integrating different aspects of the complete system.

F. Representing the Entire System

The entire system can be represented using an undirected or directed graph. This can be called a dependency or functional dependency graph. See figs. 3,4 and 6. The concepts of system modularization through decomposition and those of structural hierarchy can be shown using this structure or other structures.

For the sake of simplicity, an undirected graph can be used. This can express undefined detail. The depth of the graph is related to what is being shown and the level of detail required as regards the interrelationships. I.e. a metro line e.g. line 1 will normally have relationships with the other lines because at certain stations these lines converge or form a meeting point for switching over to the other line. The inter relationships at the middle level indicate the relationships between the metro lines. Fig. 6 is a simplification of this. Once the whole view is complete then the individual micro views are easier to construct.

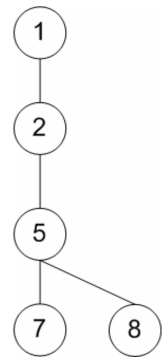

Fig. 4 ordered sub-path

For showing the micro view the individual lines are isolated. Different modeling techniques, ranging from static to dynamic, can be used for representation at this level. In this case, it was chosen to use a working model. In this case timed Petri nets have been considered because of their usefulness. But other modeling techniques can be used. A timed Petri net can be constructed for each individual line. Such a Petri net is easier to examine in isolation and can be used for time measurements.

G. Some Assumptions

When modeling complexity, the focus on important details means that some other aspects of the system are ignored. Some assumptions for the metro system are listed below.

The main assumptions for the macro and middle level are: i)the system is decomposable, ii)different notations or representation is possible, iii)system follows graphical decomposition, iv) system can be represented using graphs, complex graphs or some sort of network topology, v) graphs must contain useful information about the system, vi) symbolic notations and representation can be used, vii) it is possible to isolate and decompose parts of the graph to bring greater detail and ignore unnecessary details.

For the micro level the assumptions must be more refined and detailed. I.e. the assumptions refer to the actual operations of the system. In this case the France Paris metro is considered, hence these assumptions relate to the workings of this system. The assumptions for the France Paris individual lines are are: i) trains stop at all stations i.e. destinations, for each line only 1 train stops at a fixed time at a station for a single direction (i.e. max 2 trains but opposite directions in a station stop), ii) metro stop is associated with a Petri net place, each line forms a complete circuit. I.e. 2 circuits in opposite directions, iii) station spread is evenly distributed, behavior is highly cyclical and deterministic. I.e. fixed at the micro level, iv) system can be decomposed further.

V. Implementation

The implementation of the solution is explained using the ideas elaborated in the previous part and by diagrams.

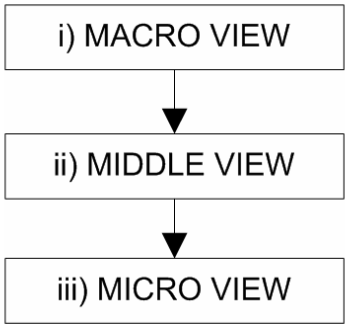

Fig. 5 three level view

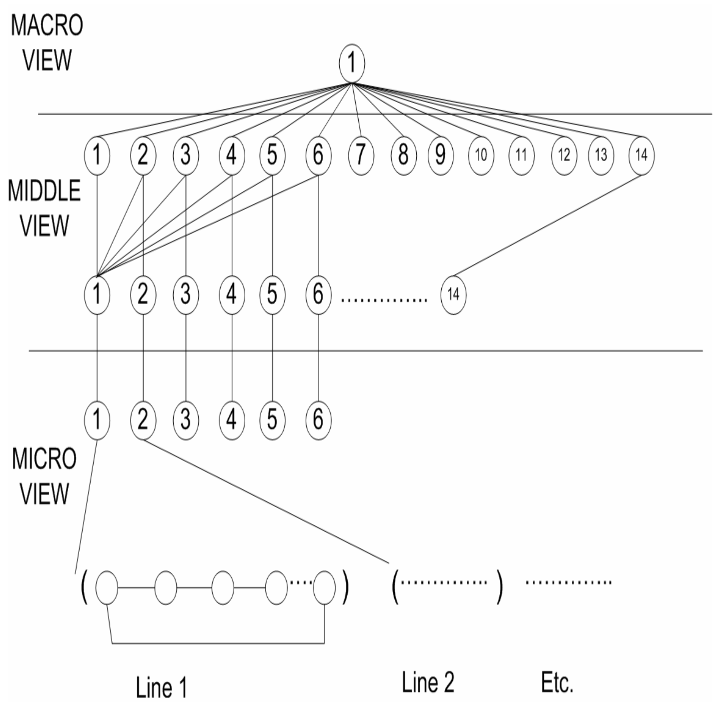

Fig. 6 partial dependency graph showing different views

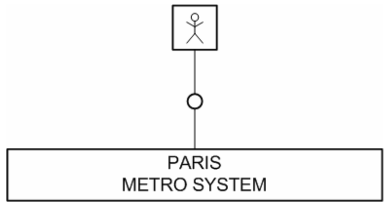

Fig. 7 paris metro top view

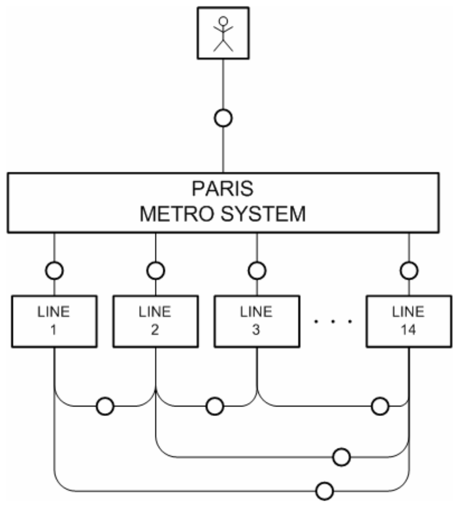

Fig. 8 paris metro top + middle view

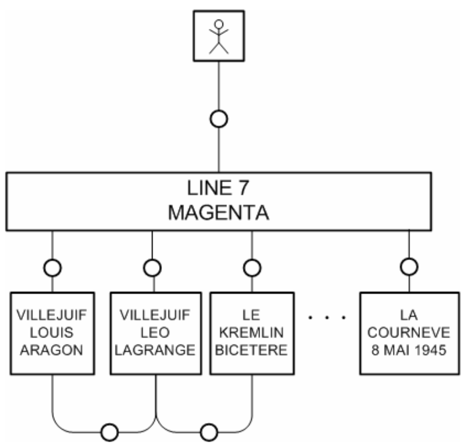

Fig. 9 low level view paris metro line 7

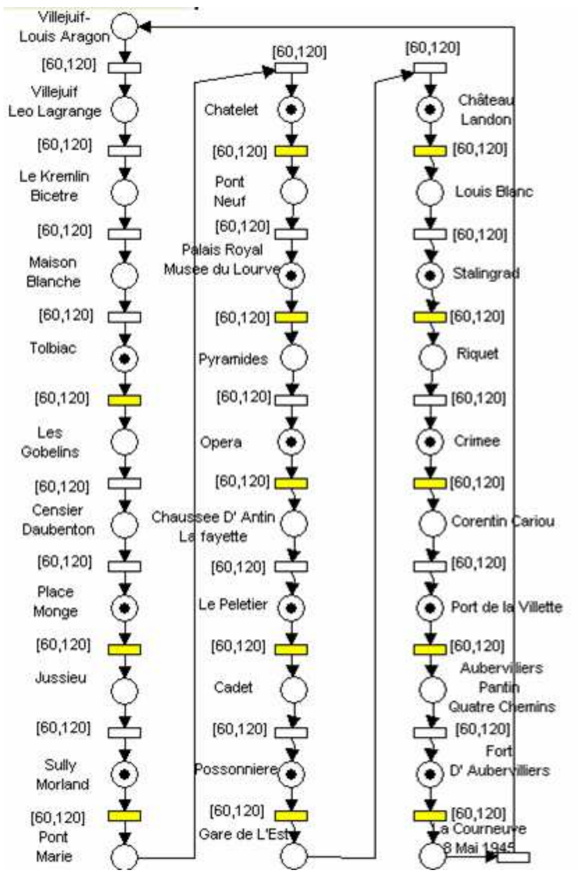

Fig. 10 time petri net for line 7 magneta

To illustrate the solution the entire Paris-Metro system is considered from the three views already mentioned and shown in fig. 7-9. The implementation can be summarized into three main parts which are the i) complete system, ii) different levels or modules that capture the requirements of these levels and iii) the low level representation which is functional. The idea of these three parts is that this approach can be replicated for similar systems.

The implementation shown is only a small part of what can be implemented. I.e. the same policy used here can be applied for all the lines and many other notations could be used for representational purposes.

A. Complete System

The complete system is composed of different views. The i) top view, ii) middle layer view and the iii) low level view. These are fig. 7-9. However to depict the complete system the description is more representational than functional. Different diagrams or notations can be used for this representation ranging from block diagrams, data structures, UML notations and object oriented notations. I.e. conceptual class diagrams, component diagrams, etc. are all useful in this respect.

Fundamental modeling concept (FMC) block diagrams are used to drawn and show the compositional structures of the three main levels described in the problem solution part [5]. Other block diagrams or notations are also valid. The FMC diagrams show the active system components which connect to one another using undirected edges via undefined channels. The channels are undefined for the sake of simplicity. These diagrams can be refined or decomposed further to show whatever detail is necessary. See fig. 2-4

To clarify the whole system a dependency graph is also used to decompose the system into its sub parts which are the individual lines. This is shown clearly in fig. 5, where the main lines of the Paris-Metro lines 1..14 are included. As these lines overlap or connect at certain stations there are other relationships which must be included. This can be compared with the actual system map.

The complete system being composed on the middle layer and low level view is more abstract than the other layers. The view of this layer can be summarized.

B. Different Levels

The structures used to represent the complete system also show the different levels. The different levels mainly show the top + middle view. In the implementation the middle level is important because it is what binds the top level to the lower level. The middle level is an important layer of information that explains the main points of the system but still from a structural level. Sometimes it can be unclear as what is actually being shown because it can overlap with the top and bottom parts.

In the case of the Paris metro system the middle level is composed of all the lines that form the metro. I.e. the middle level is composed of lines 1..14. There can be some other relationships between the lines at the middle level. The middle layer can be considered to contain the complete metro networking system and all the relationships between different lines and stations should be included. This has not explicitly been shown in the diagrams except in the partial dependency graph. Obviously more details have to be used to explain this relationship.

C. Low Level Functional Representation

The low level representation is the micro level or microscopic level of implementation. The individual lines are more important and functionality is needed. Time Petri nets, higher order nets or notations like colored Petri nets are suitable for representing the sub-systems at this level. Petri nets are a well known formalism that have received considerable attention. Petri nets have been extensively used for the static and dynamic modeling of systems ranging from computer networking to manufacturing and traffic modeling [8],[14].

Time Petri nets are executable and results can be derived from these. For each of the individual lines at the micro level a time Petri net can be constructed as in fig. 9.

Here only the time Petri net for the Paris Metro line 7 Magenta is shown and only 1 direction is considered for simplicity. The other direction is the inverse of this. Time can be associated with places, transitions or arcs. The time values are obtained randomly from a range of min 60 secs - max 120 secs which are close to the real system scenario. For a transition to occur to the next state, the next stop must be free or empty. Control dependence implies this.

Similarly for each metro station in the same direction we could have two rules i) for entry, ii) exit, these rules are logically dependent. Dependency ordering does contain memory order which in the case of such a system is likely fixed and constrained. Starvation or deadlock in the Petri net is avoided because being cyclical, at a certain point tokens representing the trains must be removed by a transition deterministically, even though time can vary. So transitions must fire only if the logical ordering is correct. The Petri net is verifiable using different techniques.

VI. Some Results And Findings

The three levels used in fig. 2-4 clearly separate the requirements and abstract the necessary details of the system. They can be combined with other notations as required.

The partial dependency graph shown in fig. 6 shows how the system is structured and is useful for developing other models and scenarios. Additionally the hierarchy exhibited, reflects interesting parallelisms with other common place computer system structures. This means that the system can be treated as many other computer related domain problems. The aspect of decomposition implies that this problem is solvable. It can be broken down into smaller parts that can be individually represented and solved. The partial dependency graph indicates the relationship between these parts. Relationships can be cyclical in nature.

The time Petri net given in fig.10 is executable and is useful for generating random time sequences for the system. The tokens placed in the places show precisely the distance of one metro train from another. A simple equation can be used to determine the avg time from one station to another where Tact =max time from one station to another and N = no of stations. Avg Time $= \frac{\sum T_{\max}}{N}$ As the system is bounded it is possible to generate a limited sequence of sequences, test codes or situations that are verifiable and well ordered. The Petri net can be called a simple transport process event Petri net. The net can be reduced to an augmented marked graph. Place and transition invariants can be found for the net. Many other forms of analysis on the time Petri net can be conducted

The Petri net can be considered as a special bipartite directed graph and further analysis can be performed on it. It can also be reconstructed using different details for other modeling purposes. The Petri net can be considered to be a precedence graph or task graph with specific constraints. There is a partial ordering of the tasks which are to be performed. The tasks imply stopping at the stations. This is observable from the precedence relation visible in fig. 10 which shows e.g. that *palais royal* is before *pyramides* and then *opera* followed by *chaussee d' antin la fayette.* This can be written as *palais royal< pyramides< opera< chaussee d' antin la Fayette.* The precedence graph is observable from the Petri net, this is in the form of a chain implying that only sequential behavior is possible. The time value placed next to the transition shows the minimum and maximum possible delay. The delay represents the actual time for the metro train to make it from one stop to another. The actual time for the train to travel from one stop to another represents the deadline for that job.

VII. Discussion

A logical model pattern for decomposition is visible from the approach being used. This work shows that object oriented modeling is quite useful for other applications like transport systems and not just only for software design and development. This seems to be familiar with a model used in object oriented design. Five or four layers used in object oriented modeling can be considered. These are i) subject layer, ii) class or object layer, iii) structure and attribute layer and iv) service layer. In a more simplified form this implies that the structure consisting of the subject, object and attribute are considered independently from the behavior or service part. This has been shown clearly to be the case in this work.

Principally this implies separating the structural aspects from the behavior of the system. This would help with clearly identifying the problem domain and understanding it. Many problems benefit from object oriented modeling even though the actual solution or implementation can take a different form.

Another important aspect is the graphical nature of the visual models shown. All these can be considered to be some form of graph. There are other ways of representing graphs and these can be formalized using various techniques.

The time Petri net representing the functional lower level, indicates the real-time properties of this system. There are certain deadlines that have to be met for the proper behavior and timeliness of the metro. There is a sequential temporal ordering between the stops. Each stop has a temporal dependency, this is the time distance it takes to travel from one station to another. The time Petri net can properly represent this and it can be used to generate results through simulation.

VIII. Conclusions

The approach presented here is useful for constructing visual models for the levels. The views show the mixed parallelism issues found in a complex transport like a metro. Different notations from object oriented analysis and design are useful for modeling the static part from a conceptual and logical point of view.

The method of combining formal theory with operational issues strives to strike a balance between the formality aspects and simplicity.

The availability of system tools, case tools, graph theory literature, Petri nets, modeling formalisms, etc. allows for the experimentation with different configurations and different views of the system. Different views can help to discover new models and processes.

Constructing and putting the models together is a considerable process that requires patience and thinking. In this aspect this is a form of knowledge discovery process that enables one to properly form and verify his experiences and comprehension about the system.

Obviously considerable work can be done to improve the notations and methods outlined in this paper. The importance of having a domain expert's advice and knowledge for improving the models is a must. The notations used are regular and basic ones. There is no point in limiting the analysis of such complex systems to a particular set of notations.

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