An Ontology for Multi-Modal Transportation Planning and Scheduling

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Abstract

In this report we present an ontology for Multi-Modal Transportation Planning and Scheduling. We take, as our starting point, the previously developed OZONE scheduling ontology, which provides a general basis for formulating scheduling domain models. We extend this core framework as necessary to capture the essential characteristics and constraints of multi-modal transportation planning and scheduling, and then use this extended framework as a basis for elaborating concepts of particular relevance to transportation planning and scheduling. Though we define a fairly large base of transportation planning and scheduling terms, our intension has not been to produce an exhaustive domain ontology. Rather our primary goal has been to define the representational framework and ontological basis for comprehensive modeling and solution of multi-modal transportation planning and scheduling problems.

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Chapter 1

Introduction

The development of effective decision support tools for predicting and controlling complex processes like the military transportation system requires, first and foremost, an ability to represent important domain elements and to formulate accurate, interpretable process models. The realization of this capability has been the broad focus of recent work in the area of ontology development and common plan representations. Historically, the construction of domain and process models has been approached in a customized (and often ah hoc) fashion, in the context of developing a specific decision support capability. The resulting models are often quite cryptic, biased by specific problem solving needs, difficult to comprehend by anyone other than the original developers, and hard to assess and validate. Work in ontological engineering, in contrast, seeks to provide a more natural and intuitive modeling basis, making models more transparent and reusable across decision support applications.

In brief, an ontology can be defined as a vocabulary (or a set of concepts and terms) for describing some domain of interest. Though not pre-requisite to the definition of an ontology, one desirable feature from the standpoint of problem solving and decision support is the structure and basis that an ontology provides for constructing executable (or machine interpretable) models of a given domain. One measure of the utility of an ontology is the scope and types of inferences that it supports, and one important perceived role of ontologies is in providing a basis for structured domain modeling and knowledge acquisition.

Previous work in the development of ontologies for planning and scheduling has for the most part taken this perspective, but has focused principally on the development of general-purpose, core ontologies that are applicable in a broad range of domains. These core ontologies can provide useful starting points for constructing models in any particular planning and scheduling domain, but ultimately what is required is a "drilling down" and elaboration of more specialized domain ontologies.

In this paper, we take one step in this direction and develop a specialized domain ontology for military transportation planning and scheduling. The ontology that is developed centers around five basic components: (1) MOVEMENT REQUIREMENTS, which represent input requests for TRANSPORT SERVICES, (2) TRANSPORT SERVICES, which define the set of capabilities that the transportation system provides, (3) TRANSPORT ACTIVITIES, which use RESOURCES to perform TRANSPORT SERVICES and satisfy MOVEMENT REQUIREMENTS, (4) RESOURCES, such as TRANSPORT VEHICLES, CREWS and TERMINAL FACILITIES, and (5) CONSTRAINTS, which dictate how, when, by whom and where TRANSPORT ACTIVITIES can be executed. The concepts defined in the ontology are targeted towards modeling the characteristics and requirements of global, multi-modal transportation planning and scheduling processes, but also reflect our prior experience in strategic deployment scheduling and aeromedical evacuation (re)planning. Although we define a fairly large base of transportation planning and scheduling terms, our primary goal is to provide the necessary ontological infra-structure for representing the important aspects of different transportation planning and scheduling applications.

The remainder of this document is organized as follows. In Section 2 we first provide a brief overview of the application domain which has served as the primary driver of our ontology development effort: the multi-modal transportation planning and scheduling problem faced by the US Transportation Command. In Section 3, we then briefly review contemporary ontology and common plan representation development efforts from the standpoint of the relevance to this driver domain. Our principal conclusion here is to adopt the OZONE scheduling ontology as a starting basis for elaborating a transportation domain ontology and to use concepts from other ontology building efforts to extend its coverage to include planning, agency and authority concerns. Next, in Section 4, we summarize the basic components of the OZONE ontology. The transportation planning and scheduling domain ontology is then presented in detail in Section 5. Finally, in Section 6, some concluding remarks are made.

Chapter 2

The Multi Modal Transportation Problem

The success of military operations and campaigns depend on reliable, effective, and timely deployment of forces, equipment, and on continuous support during the entire campaign. A critical part of this support is a transportation logistics infrastructure that would manage, coordinate, and optimize transportation resource usage; guarantee visibility over operations; and react to unexpected events in order to avoid disruption of service. This transportation infrastructure is what we call a **TRANSPORTATION SYSTEM.**

A transportation system is composed of three basic elements: (1) the **MODE OPERATIONS** (air, sea, or land); (2) the **TERMINAL OPERATIONS;** and the (3) **MOVEMENT CONTROL.** The movement control is the critical components of the system. It coordinates the transportation assets of all modes as well as terminal usage. We will refer to the process of planning, routing, scheduling, and controlling transportation assets, and maintaining in-transit visibility to assist commanders and operations staffs in force tracking as **MOVEMENT CONTROL.** [Joint-Pub-4-01.3, 1996]. According to this definition, the movement control process involves **PLANNING, APPORTIONING TRANSPORTATION, ALLOCATING TRANSPORTATION, DECONFLICTING PRIORITIES, VALIDATION OF REQUESTS, COORDINATION,** and guaranteeing **IN-TRANSIT VISIBILITY** as well as **FORCE TRACKING.**

A request for moving personnel or cargo in a military operation is a **MOVEMENT REQUIREMENT.** Movement requirements are established by the competent authority and can be fulfilled using one or more **MODE OF TRANSPORTATION.** Land, air, and sea are the generic transportation modes. Despite similarities, each transportation mode has its own characteristics.

MOVEMENT REQUIREMENTS can be generated as a result of transportation needs to execute routine daily military and civil operations during **PEACE-TIME;** can be generated to support military exercises – **CJCS-Sponsored** (The Chairman of the Joint Chiefs of Staff), or **CINC-Sponsored** (Commander in Chief) exercises; or can be generated to support **WARTIME** and **CONTINGENCY** operations. Therefore, movement control can be classified as **CRISIS ACTION STRATEGIC MOVEMENT CONTROL** and **PEACETIME MOVEMENT CONTROL.** It is desirable that transportation procedures and responsibilities remain unchanged regardless the type of operation being conducted. This would allow transportation personnel to be trained for wartime operations during peacetime routine daily activities. The main difference between peacetime and wartime operations would be related to volume and intensity. The planning process however, is considerably different.

The planning and execution of transportation activities is affected by the nature of the military operation or **CAMPAIGN** being performed. A **CAMPAIGN** is a series of related military operations aimed at accomplishing a strategic or operational objective within a given time and space. **CAMPAIGN PLANNING** is the process of translating strategies and objectives into a set of executable operations.

During a military campaign, there could be four phases or types of transportation activities: **DEPLOYMENT** that corresponds to the relocation of forces and material to the area of operations; **SUSTAINMENT** that is defined as the provision of personnel, logistics, and other support required to maintain and prolong operations or combat until accomplishment or revision of the mission objectives [Joint-Pub-5-03.1, 1993]; **EVACUATION** of patients, prisoners of war, and non-combatant personnel from the area of operations to a medical facility or to a safe area; and **RE-DEPLOYMENT** defined as the transfer of a unit, an individual, or supplies deployed in one area to another area, or to another location within the area, or to the zone of interior for the purpose of further employment[Joint-Pub-1-02, 1994]. These phases can then be further decomposed according to the characteristics and requirements of the transportation activities involved. We will focus on the force deployment and sustainment phase as a means of presenting the ontology for the multi-modal transportation problem.

Control of force deployment and sustainment is composed of **STRATEGIC MOVEMENT CONTROL** and **THEATER MOVEMENT CONTROL.** Strategic movement corresponds to the activities related to **PRE-DEPLOYMENT,** movement from the unit **ORIGIN** to a **PORT OF EMBARKATION**(POE) within the United Stated, and the **STRATEGIC LIFT** from the port of embarkation to a **PORT OF DEBARKATION** (POD). Theater movement control during deployment includes **IN-THEATER RECEPTION** at the port of debarkation, and **THEATER ON-WARD MOVEMENT.**

The planning for movement control follows different processes according to the focus and nature of operations. These planning processes are currently supported by the *Joint Operation Planning and Execution System (JOPES)* and the description here presented follows the terminology used in JOPES' manuals and publications[Joint-Pub-5-03.1, 1993]. The two main process types are **DELIBERATE PLANNING** and **CRISIS ACTION PLANNING .** Campaign planning is a more general process that begins with deliberate planning and continues through crisis action planning.

The deliberate planning process focuses on the *time-phasing of movements and the assigning of transportation resources to support initial deployment for a set period, normally around 90 days after deployment commences* [Joint-Pub-4-01.3, 1996]. This process is divided into five phases: **INITIATION, CONCEPT DEVELOPMENT, PLAN DEVELOPMENT, PLAN REVIEW,** and **SUPPORTING PLAN DEVELOPMENT.** According to the nature of requests, four different types of plans can be created: **OPERATION PLAN** (OPLAN), **OPERATION PLAN in CONCEPT FORMAT** (CONPLAN) without **TIME-PHASED FORCE and DEPLOYMENT DATA** (TPFDD), a CONPLAN with TPFDD, and **FUNCTIONAL PLANS.** An OPLAN is a more detailed version of an CONPLAN and always has a TPFDD. The TPFDD is a computer database used to identify types of forces and actual units required to support operation plans and operation orders. The TPFDD establishes the sequence for moving the forces and their support into the **AREA of OPERATIONS** and provide the basis for transportation schedule generation.

The crisis action planning differs from deliberate planning as a result of the small amount of time available to reach allocation, scheduling, and identification of threats to transportation assets. This process is divided into six sequential phases: **SITUATION DEVELOPMENT, CRISIS ASSESSMENT, COURSE of ACTION DEVELOPMENT, COURSE of ACTION SELECTION, EXECUTION PLANNING** and **EXECUTION.** The result of this entire process is a set of campaign plans and **OPERATION ORDERS** (OPORDS) to be executed. The details of the planning process and respective plan formats are beyond the scope of the current work.

Chapter 3

A Selected Review of Ontology Development Efforts

In determining an ontological base from which to develop a domain ontology for multi-modal transportation planning and scheduling, there is a range of recent work in ontology and common plan representation development that can be considered and drawn upon.

Two representative examples of work in the area of common plan representations are the OMWG Core Plan Representation model [Pease & Carrico, 1997] and the current DARPA SPAR (Shared Planning and Activity Representation) development effort [Tate, 1997]. Broadly characterizing both of these efforts, the principal thrust has been on the development of a core planning model that is broadly applicable to many planning domains. This has led to development of fairly general "upper models", which synthesize the commonality of many more comprehensive modeling efforts and omit those more idiosyncratic aspects of more specialized planning representations. In some cases, the focus of the developed models is expanding; for example, work aimed at expanding the OMWG representation to encompass a number of logistics and military planning domains is currently underway. Nonetheless, common plan representation models tend to provide mainly high-level modeling distinctions and are not currently elaborated to a level of detail that is needed to productively describe substantial planning domains like multi-modal transportation. In particular, these models have either ignored the specification of resource models or have treated them only superficially.

A different set of ontology development efforts have considered the development of more substantial resource models. The TOVE Enterprise Ontology [Fadel, M.S. Fox, & Gruninger, 1994, Gruninger & Fox, 1994] defines a fairly comprehensive (although not particularly scalable) model of a simple capacity resource and other "scheduling-related" efforts (e.g., [Le Pape, 1994]) have defined a number of additional types of resource models. Perhaps the most substantial ontology developed to date from the standpoint of scheduling and resource allocation is the OZONE scheduling ontology [Smith, Lassila, & Becker, 1996]. The OZONE scheduling ontology is the result of considerable prior experience in building planning and scheduling systems, in application domains ranging from manufacturing production scheduling [Smith, 1994] to space mission planning [Muscettola *et al.*, 1992] to military deployment and aero-medical evacuation (re)planning [Smith & Lassila, 1994, Lassila, Becker, & Smith, 1996]. The class library design and implementation underlying the OZONE framework (and the ontology which provides its conceptual foundation) have followed from retrospective analysis of these scheduling domains and systems (e.g., [Becker & Díaz-Herrera, 1994]), together with application of object-oriented analysis and design principles [Smith & Lassila, 1994].

Both the fact that OZONE ontology has evolved from experience in a wide range of scheduling domains and the fact that it has been previously applied to related transportation scheduling domains make it a natural starting point for elaborating a transportation planning and scheduling domain ontology. At the same time, this ontology derives principally from a "scheduling system" perspective and, as such, has not paid substantial attention to issues relating to goal representation and expansion, activity network synthesis, agency and ownership. All of these issues, which require consideration in developing a complete model of the multi-modal transportation planning and scheduling domain, have a more central role in the planning representations mentioned above. Accordingly, we will draw on concepts from these planning representations to appropriately extend the core OZONE ontology in these areas.

Chapter 4

The OZONE Scheduling Ontology

We take the OZONE scheduling ontology as our starting point for elaborating a transportation planning and scheduling domain ontology. Generally speaking, The OZONE scheduling ontology can be characterized as a meta-model of the domain of scheduling. It provides a language for describing those aspects of the scheduling domain that are relevant to construction of an application system, and a set of constraints on how concepts in the language fit together to form consistent domain models. Consistency, in this context, relates to the information and knowledge required to insure executability of the model. Generally speaking, the ontology serves to map user-interpretable descriptions of an application domain to application system functionality.

This linkage is established within the OZONE ontology through the inclusion of *properties* and *capabilities* as an integral part of concept definition. Properties correspond to the attributes of an entity. Static properties are those whose values are supposed to hold during a certain period of time or during the entire existence of the entity. Speed and size are examples of properties. The speed of a transportation resource can change over time but, for scheduling purposes, it can be very well approximated as a constant over certain periods of time. Similarly, the physical dimensions of most transportation resources are not expected to change and can also be considered as static properties. Dynamic properties are attributes whose values vary or evolve over time, such as the availability of a resource.

Capabilities are related to the problem solving behavior *implemented* by the entity. They provide an operational semantics to the concepts defined in the ontology, in a form that reflects a specific bias with respect to application system design. In particular, the OZONE ontology presumes an underlying constraint-based solution framework and scheduling system architecture [Smith, 1994, Smith, Lassila, & Becker, 1996]; this commitment follows directly from the strong match of constraint-based techniques to the decision-support requirements of practical scheduling environments. Capabilities, then, encapsulate reusable components for configuring and customizing constraint-based solution methods. For example, the concept of a “resource” contributes capabilities for querying and managing its available capacity over time, and different resource types (e.g., reusable, consumable) provide specific “implementations”. Given a solution method that incorporates these capabilities, the ontology provides a direct basis for its customization to match the resources in any target domain.

According to [Tate, 1997], a *relationship is an association between two or more entities, and are separate entities in their own right rather than being incorporated into attributes or properties of the entities related.* In OZONE however, relationships other than constraints are not explicitly represented. Including them in the presentation of the ontology would require an extra terminology that is not supported by the underlying implementation. Therefore *relations* among different entities are presented as properties of both entities. Using [Tate, 1997] example, the relation *performs (activity, agent)* is represented by the activity having an agent property, and by the agent having an activity (or activity to perform) property.

In the remainder of this section, we summarize the basic components of the OZONE scheduling ontology. By convention, we use capitalization to distinguish specific concepts that are included.

4.1 Basic components of OZONE scheduling models and their relationships

Like several contemporary process modeling and ontology development efforts [Uschold *et al.*, 1996, Gruninger & Fox, 1994, Le Pape, 1994, Lee, Yost, & Group, 1994, Tate, 1996, Smith, 1989] the OZONE ontology adopts an activity-centered modeling viewpoint and is biased towards constraint-based scheduling generation. Scheduling is defined as a process of feasibly synchronizing the use of RESOURCES by ACTIVITIES to satisfy DEMANDS over time, and application problems are described in terms of this abstract domain model. Figure 4.1 illustrates the base concepts involved and their structural relationships. A DEMAND is an input request for one or more PRODUCTS, which designate the GOODS or SERVICES required. More generally, the DEMAND is the interface that allows an external client to state the objective to be achieved as well as certain user specified restrictions and/or preferences on this objective. The objective specified in the DEMAND is the expected output of the system. For example, if a customer orders a computer from a computer manufacturing company, the output expected by the user from the company is the computer with the configuration specified in the order. If the computer manufacturing company contracts a transportation company to deliver the computer to the customer, the result expected from the transportation company is the movement or transfer of the computer location from the factory to the customer specified delivery address. This expected system output is the PRODUCT. The product can be a physical entity like the computer ordered; or the satisfaction of some conceptual specification like the transfer of the location of an object, or even some more abstract goals that have no actual physical meaning.

The ability to generate the expected output according to specifications is a property of the system. A computer company can assemble only a certain range of configurations and a transportation company can support only certain types of cargo. The different types of objectives that can be accomplished by the system characterize the set of PRODUCTs available to the user of that particular system. In the OZONE ontology, the PRODUCT entity represents the knowledge required by the scheduler to generate a set of resource allocations over time. A scheduling system does not generate any physical object nor produces any change in the real world. The production and the transportation systems are the entities responsible for the actual accomplishment of the objective. In a scheduling system, the PRODUCT encodes the internal information about resources and physical characteristics of the process that when combined with the external demand allows the generation of a set of RESOURCE requirements over time. These resource requirements are the ACTIVITIES. Therefore, the PRODUCT can be seen as the template plan for accomplishing a certain goal or a certain set of goals. The DEMAND provides the parameters that maps this prototypical plan into an ACTIVITY network that when executed would accomplish the specified objective.

The satisfaction of DEMANDS centers around the execution of ACTIVITIES. An ACTIVITY is a process that uses RESOURCES to produce goods or provide services. An ACTIVITY can only be executed if certain conditions, like resource availability, are satisfied. The execution of an ACTIVITY produces changes in the state of the real world. Notice that although PRODUCTS are "produced" as a result of the execution of activities, they play a different role in the OZONE ontology. They represent the set of valid objectives that can be specified in a demand; the set of objectives the system knows that can be satisfied with the set of RESOURCES available. The PRODUCT entity act more as a link connecting DEMANDS to ACTIVITIES through RESOURCES than a means of describing the result of executing activities. Using our example, the PRODUCT for the computer manufacturing scheduling system is the process plan for producing the configuration specified. When the order is input into the scheduling system, the PRODUCT has the information necessary to create a process plan that when executed would produce the required computer. The scheduler only allocates time on the resources specified in the plan.

The use of RESOURCES and the execution of ACTIVITIES is restricted by a set of CONSTRAINTS. These CONSTRAINTS can be specified by the DEMAND, like release date and due date; can be inherent to the PRODUCT characteristics, like technological restrictions and design parameters; or can be a result of the RESOURCE limitations, like resource capacity, speed and accuracy.

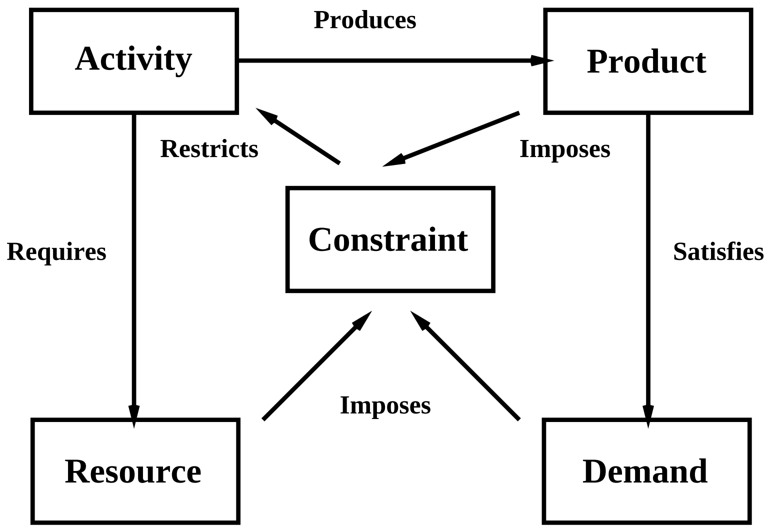

Figure 4.1: Abstract Domain Model

These five base concepts of the ontology - **DEMAND, ACTIVITY, RESOURCE, PRODUCT,** and **CONSTRAINT** - together with the inter-relationships depicted in Figure 4.1, define an abstract model of a scheduling domain, and a framework for analyzing and describing particular application environments. Associated with each concept definition are terminologies for describing basic properties and capabilities. Properties define attributes or parameters of relevance to specifying an executable scheduling model. The abstract model and its properties are extensible through concept specializations to define more specific models for various sub-domains.

Chapter 5

A Transportation Planning and Scheduling Ontology

Figure 5.1 indicates the basic specialization of the OZONE abstract model for the transportation planning and scheduling domain. In this domain DEMANDS are referred to most generally as MOVEMENT REQUIREMENTS, and represent input requests for TRANSPORT SERVICES. A TRANSPORT SERVICE is the basic PRODUCT of the transportation system, and the execution of TRANSPORT ACTIVITIES leads to achievement of TRANSPORT SERVICES and the satisfaction of MOVEMENT REQUIREMENTS. Transportation RESOURCES are diverse and varied, including VEHICLES, CREWS, ON-LOAD and OFFLOAD equipment, and STORAGE FACILITIES.

In the following subsections, we consider the definition of these basic components of transportation planning and scheduling models individually and in more detail. Each subsection is organized so as to first provide a specification of the abstract concept from which the domain concept has defined, and to then elaborate characteristics of the domain concept itself.

Before proceeding to a discussion of DEMANDS and MOVEMENT REQUIREMENTS, we introduce some basic temporal concepts that are to be assumed.

5.1 TEMPORAL PRIMITIVES

In what follows, we assume the existence of basic temporal concepts such as TIME-INTERVALS and TIME-POINTS (c.f. [Allen, 1984]).

Additional useful time concepts are:

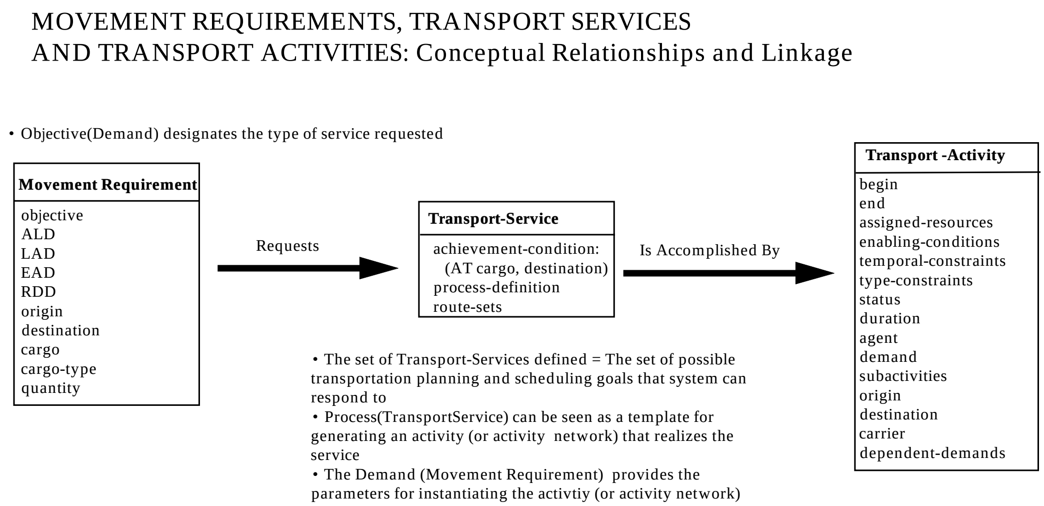

Figure 5.1: Transportation Domain Specialization

CALENDAR: a system for dividing up time that establishes a point of reference and units for counting time.

TIME-UNIT: The granularity of the time representation. It could be one hour, one minute, one second, one day.

DATE: a fixed point in time defined in relation to a certain CALENDAR. A DATE is a constant and cannot be changed.

TIME-POINT: a variable representing a point in time. The value of a TIME-POINT can be a DATE or an offset in relation to the origin of time. Changing the value of a TIME-POINT does not change the DATE that was previously associated to it.

CURRENT-TIME: the TIME-POINT which value reflects the current DATE according to the calendar used.

TIME-ORIGIN: the TIME-POINT which value is the DATE used as a reference or origin for counting time. TIME-ORIGIN is also referred as TIME-ZERO.

TIME-HORIZON: the number of time units between CURRENT-TIME and a point in time beyond which scheduling decisions are not important or should not be considered.

TIME-INFINITE: the largest number of time units that can be used.

Some useful military terms for describing specific time point are [Joint-Pub-5-03.1, 1993]:

C-day: The unnamed day on which a deployment operations commences or is to commence.

D-day: The unnamed day on which a particular operation commences or is to commence.

M-day: The unnamed day on which full mobilization commences or is to commence.

N-day: The unnamed day an active duty unit is notified for deployment or re-deployment.

R-day: The unnamed day on which re-deployment of major combat support and combat service support commences or is to commence.

S-day: The day the President authorizes Selected Reserve call-up.

T-day: The day the President declares National Emergency and authorizes partial mobilization.

W-day: The day the adversary begins preparing for war.

F-hour: The effective time of announcement by the Secretary of Defense to the Military Departments of a decision to mobilize Reserve Units.

H-hour: The specific hour on D-day at which a particular operation commences or is to commence.

L-hour: The specific hour on C-day at which a deployment operation commences or is to commence.

5.2 DEMANDS

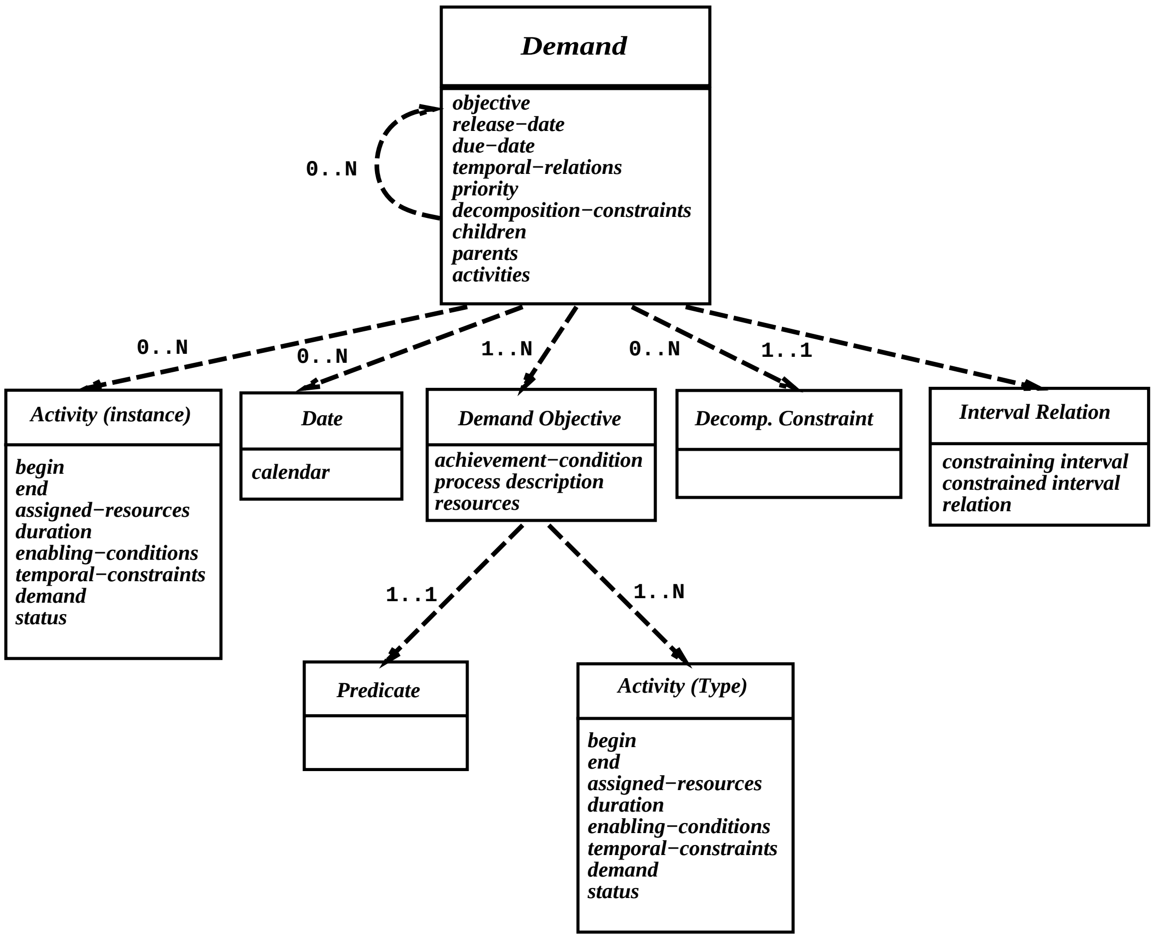

Figure 5.2: Demand

5.2.1 Concept Definition.

A **DEMAND** is a request for goods and services, or more generically PRODUCTS, that the system being modeled can provide. DEMANDS specify the input goals that drive the system, along with any CONSTRAINTS that must be taken into account when achieving them. The set of outstanding DEMANDS at any point determine the current scheduling problem to be solved.

The DEMAND entity is the input interface between an external user and the system. DEMANDS are satisfied by executing the corresponding activity networks established by the PRODUCT type, or kind of service, requested. All the CONSTRAINTS specified in the DEMAND are translated into CONSTRAINTS on the scheduling and execution of ACTIVITIES. In this sense, DEMANDS are unconstrained. DEMANDS just specify CONSTRAINTS. The explicit representation of CONSTRAINTS is at ACTIVITY level.

In principle, all DEMAND properties can be specified by the user. Some of the properties are optional and default values can be used if they are not specified. Some properties are required and an error should be signaled if they are not specified.

We will refer to the amount of information specified in the demand as the **LEVEL OF SPECIFICATION** of the DEMAND. At the highest level of specification, there would be a one-to-one mapping from DEMAND to ACTIVITIES and there would be no need of any scheduling since the DEMAND would precisely specify all the required RESOURCE allocations. As we move to lower level of specification, less information is provided in the DEMAND description and more problem solving activity is be required. For example, in the transportation domain, if a DEMAND specifies the RESOURCE type, ORIGIN, PORT-OF-EMBARKATION, PORT-OF-DEBARKATION, and DESTINATION, the scheduler would only have to find one resource of the specified type that satisfies the time constraints. In this case we would have a specification at the resource allocation level. If neither PORT OF EMBARKATION not PORT OF DEBARKATION is specified, the mode of transportation would have to be also selected and a more elaborated algorithm is required. In this case, we would have a specification at the mode selection level. The labeling of the different specification levels is highly domain dependent. The one we used in our example is based on the problem solving capabilities of the underlying scheduling system. We could also, for example, just refer to these different levels of specification by a number. The minimum amount of information required to generate a solution would be referred to as LEVEL OF SPECIFICATION 0. There will be as many levels as the number of different set of values that could be left unspecified until we get to a complete defined solution. The accepted LEVEL OF SPECIFICATION is a function of the implemented problem solving capabilities.

A slightly different dimension is the **LEVEL OF DETAIL** of the DEMAND. The LEVEL OF DETAIL reflects the level of abstraction of the information contained in the DEMAND. For example, the amount of cargo in a given request could be described, at a certain level of detail, by its weight in SHORT TONS. At a higher LEVEL OF DETAIL this same cargo would be described as a certain number of trucks each with a certain weight. At even a higher level the dimensions of each truck would be provided. Notice the difference between the LEVEL OF DETAIL and the LEVEL OF SPECIFICATION. The LEVEL OF DETAIL reflects the accuracy of the model and is irrelevant to the problem solving capabilities. The scheduling algorithm should be able to allocate a transportation resource for either description. The LEVEL OF SPECIFICATION however, imposes extra burden on the problem solving requirements. If information is not specified, the system must infer it to solve the scheduling problem.

5.2.2 Properties.

A DEMAND has several defining properties:

- **PRODUCT** - The PRODUCT is the object of the DEMAND. It specifies the type of good or service that is requested. The PRODUCT is usually a required property unless there is only one possible PRODUCT in the system or the default has been made explicit.
- **RELEASE-DATE** - The earliest time any ACTIVITY for achieving the DEMAND can start.
- **DUE-DATE** - The latest time any ACTIVITY for achieving the DEMAND should end.
- **TEMPORAL-RELATIONS** - These are synchronization constraints with respect to achievement of other system DEMANDS. TEMPORAL-RELATION between DEMANDS are translated into TEMPORAL-CONSTRAINTS between ACTIVITIES.
- **PRIORITY** - The relative importance of the DEMAND, providing a basis for establishing a partial ordering over the entire set of demands. The PRIORITY property is a string that identifies a pre-defined priority level of a DEMAND. The priority of a DEMAND is a relation between two DEMANDS objects and is a capability of the DEMAND. Priority between DEMANDS can also be established based on values other than the PRIORITY property. For example, we can establish that DEMANDS with earlier DUE-DATE have higher priority.
- **ACTIVITIES** - The set of activity networks that when executed would fulfill the DEMAND. As indicated earlier, these plans or networks of activities are created by *Instantiate-Product-Plan*, a joint capability of DEMAND and PRODUCT concept definitions. A DEMAND can have more than one ACTIVITY. A DEMAND with zero activities does not make much sense in most problems domains.
- **CHILDREN, PARENTS** - DEMAND is an aggregate entity. DEMAND aggregation or decomposition should be user specified. Internal aggregation and decomposition motivated by scheduling decisions is handled at the ACTIVITY level. Additional constraints can be imposed on the ACTIVITIES satisfying aggregate demands.
- **DERIVATIVE-DEMANDS** - As a result of the scheduling decisions being made, additional DEMANDS may be generated. These DEMANDS are internally generated and should disappear as soon as the decision that cause their generation has been retrieved. DERIVATIVE-DEMANDS

are not the same as DEMANDS generated as a result of splitting one large demand into smaller parts. For example, the transportation of a large amount of cargo, could be split into ten different ACTIVITIES. Conceptually, this would be equivalent to splitting the original DEMAND in ten SUB-DEMANDS. In a different line, if the RESOURCE selected to process one of the ACTIVITIES is a C-5, special CARGO-HANDLER-EQUIPMENT may be required. If no CARGO-HANDLER-EQUIPMENT is available and there are no feasible RESOURCE ALTERNATIVES, a special request for this equipment could be generated. This would generate an internal DEMAND for moving the equipment. If later, as a consequence of the development of the situation, the decision of using a C-5 is retrieved and a C-141 is used instead, the request for the CARGO-HANDLER-EQUIPMENT can be removed from the system and the user does not need to know about it.

For most types of DEMANDS, there will be additional parameters which further specify the requested PRODUCT. DEMAND parameters will vary for different types of goods or services.

5.2.3 Movement Requirements

In the military transportation domain, DEMANDS are called **MOVEMENT REQUIREMENTS.** Movement requirements are established by competent authority within the Joint Staff, the Military Departments, combatant commands, other Department of Defense and Federal Agencies, and the executive branch of the government.

A MOVEMENT REQUIREMENT is a request for moving certain amount of cargo or a certain number of passenger between two geographic locations. The information provided in the requirement could be such that the movement activity is completely specified, or some information could have been left unspecified so that alternatives are possible.

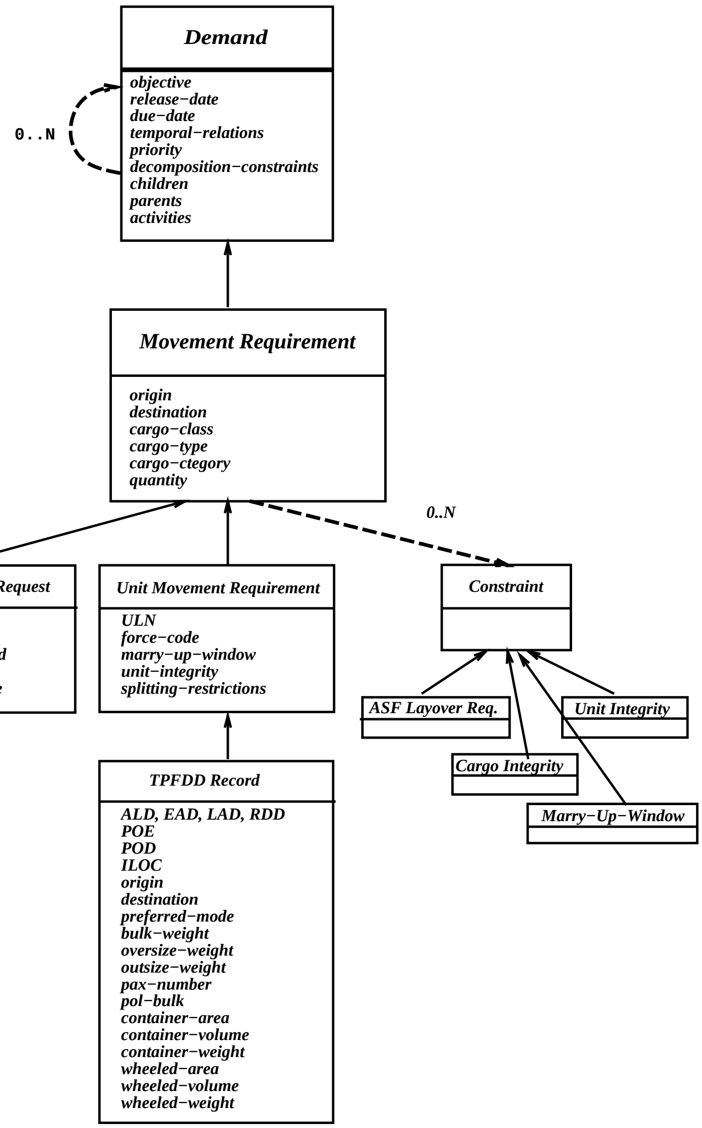

Figure 5.3: Movement Requirement Structure

Being a specialization of the DEMAND entity to the domain of military transportation, the MOVEMENT REQUIREMENT entity extends the set of properties provided by the DEMAND and also rename some of them to better reflect the terminology used in the transportation domain. The description here presented is based on the terminology used by the military to describe the fields of a TPFDD record. Figure 5.3 schematically shows the relations between DEMANDS and MOVEMENT REQUIREMENTS. We generically refer to the total amount of cargo specified in the MOVEMENT REQUIREMENT as the UNIT. The extended and changed properties are:

- Properties Renamed:
  - **READY TO LOAD DATE (RLD):** Designates the DATE the cargo of the requirement is or will be ready at its ORIGIN. This property renames the RELEASE-DATE.
  - **REQUIRED DELIVERY DATE (RDD):** Designates the last day the requirement should arrive and complete unloading at its final DESTINATION. This property renames the DUE-DATE.
- Extended Properties:
  1. *Identification Properties:* MOVEMENT REQUIREMENTS are represented by records in a TPFDD. These records have information used to identify and track the cargo to be moved. Each record or line of a TPFDD is referred to as a **UNIT ENTRY.** Some of these identification records are:
     - **UNIT LINE NUMBER (ULN):** A seven character string that uniquely identifies an entry or line in a TPFDD.
     - **UNIT IDENTIFICATION CODE:** A six character alphanumeric code that uniquely identifies the actual Active, Reserve, and National Guard unit of the Armed Forces designated to fill this requirement.
     - **FORCE DESCRIPTION:** MOVEMENT REQUIREMENTS are aggregated into **FORCE MODULES.** A FORCE MODULE is a grouping of combat, combat support, and combat service support forces, with their accompanying supplies and required non-unit resupply and personnel necessary to sustain forces for a certain period of time. The FORCE DESCRIPTION field is free format string describing the FORCE MODULE to which the REQUIREMENT belongs.
     - **FORCE INDICATOR CODE:** Alphanumeric code used to uniquely identify force entries in a TPFDD.
  2. *Time Related Properties:* These properties allow the user to establish additional constraints on the timing of the activities that would satisfy the requirement.
     - **EARLIEST DELIVERY DATE (EDD):** Computed date the first part of unit would arrive at PORT OF EMBARKATION.
     - **AVAILABLE TO LOAD DATE (ALD):** Date the unit is ready to be moved from the PORT OF EMBARKATION.
     - **INTERMEDIATE LOCATION DELAY:** Number of days the unit will delay at an intermediate location.
     - **EARLIEST ARRIVAL DATE (EAD):** Earliest day a unit may arrive at PORT OF DEBARKATION.

- **LATEST ARRIVAL DATE (LAD):** Latest day the unit must arrive and complete unloading at the PORT OF DEBARKATION.
- **FEASIBLE ARRIVAL DATE (FAD):** Computed day the last part of the unit completes unloading at PORT OF DEBARKATION.
- **PROJECTED LATENESS AT POD:** Computed number of days the unit will be late in arriving at PORT OF DEBARKATION.

3. *Location Related Properties:* The user can completely or partially define the spatial movement of the cargo by establishing ITINERARIES and ROUTES to be followed by the transportation resources moving the cargo.

   - **ORIGIN:** geographic location where the unit is initially located.
   - **DESTINATION:** geographic location where the unit should be deployed.
   - **PORT OF EMBARKATION (POE):** geographic location that designates the AIRPORT or SEAPORT from which the unit will be moved.
   - **PORT OF DEBARKATION (POD):** geographic location that designates the AIRPORT or SEAPORT to which the unit should be moved. APOD and SPOD designates AIRPORT OF EMBARKATION and SEAPORT OF DEBARKATION.
   - **ALTERNATE POE, ALTERNATE POD:** Alternative ports to be used in case POE and / or POD are overloaded or not available.
   - **INTERMEDIATE LOCATION (ILOC):** geographic location at which the transportation resource(s) carrying the unit should during the movement from POE to POD.
   - **ITINERARY:** Sequence of geographic locations, AIRPORTS and SEAPORTS, where the transportation resources are required to stop. If the ITINERARY is not specified, *ORIGIN – POE – ILOC – POD – DESTINATION* defines the itinerary to be followed.
   - **ROUTE:** Established path the transportation resource(s) should follow to satisfy the requirement. The ROUTE is not necessarily equal to the ITINERARY. For example, the ROUTE to accomplish the ITINERARY *New York – Miami – San Diego* by sea would be different if the Panama Channel is open or closed.

4. *Cargo Related Properties:* Depending on the TRANSPORTATION MODE, different terminology is used to describe the cargo in a requirement.

   - **TRANSPORTATION MODE:** Specify if the unit should be moved by **AIRLIFT , SEALIFT, or SURFACE.**
   - **CARGO CLASS:** This property generically describes the nature of the cargo being moved. There are basically five classes of cargo:

- * **SPECIAL**
  * **UNITS**
  * **RESUPPLY**
  * **AMMUNITION**
  * **POL**

  These classes are only used for SEALIFT transportation.
- **CARGO CATEGORY:** The category of the cargo provides some information about the physical structure and size of the cargo being transported. For AIRLIFT, the categories are:
  * **PAX:** Passenger.
  * **BULK** Cargo that would fit on a 463L pallet. Its maximum dimensions should be 104 inches long, 84 inches wide, and up to 8 ft. high.
  * **OVERSIZE** Cargo that would not fit on an 463L pallet but whose maximum dimensions are 1,090 inches long, 117 inches wide, and 96 inches height.
  * **OUTSIZE** Cargo larger that the dimensions specified for OVERSIZE and would only fit inside a C5.
  * **SMALL LOADS**
  * **MILITARY AIRCRAFT ONLY**
  * **AIR DROP**
  * **DIRECT DELIVERY**

  Only the first five categories are related to the capacity of the airplane. The three last categories are related to the delivery of the cargo in the AREA OF OPERATIONS or THEATER.
  For SEALIFT, the categories are:
  * **CONTAINERIZABLE**
  * **WHEELED EQUIPMENT**
  * **TRACKED EQUIPMENT**
  * **AVIATION EQUIPMENT**
  * **NON-CONTAINERIZABLE NON-VEHICULAR**
- **CARGO TYPE:** The CARGO TYPE gives details about the specific contents of the cargo in the requirement. These types are used by both SEALIFT and AIRLIFT. SEALIFT however, prefer to work with the CARGO CLASSES specified above. The CARGO TYPES and corresponding CARGO CLASSES are:
  * **AF-AIRCRAFT (cargo-class UNITS)**
  * **AF-SUPPORT (cargo-class UNITS)**
  * **AF-PREPO (cargo-class UNITS)**
  * **MARINE-PREPO (cargo-class UNITS)**

- ∗ **ARMY-PREPO (cargo-class UNITS)**
- ∗ **AIRBORNE (cargo-class UNITS)**
- ∗ **ARMOR (cargo-class UNITS)**
- ∗ **MECH-INFANTR (cargo-class UNITS)**
- ∗ **AIRMOBILE (cargo-class UNITS)**
- ∗ **CBAC (cargo-class UNITS)**
- ∗ **INFANTRY (cargo-class UNITS)**
- ∗ **ARMOR-CAV (cargo-class UNITS)**
- ∗ **AMPH-MARINES (cargo-class UNITS)**
- ∗ **NAVY (cargo-class UNITS)**
- ∗ **CS-ENGINEER (cargo-class UNITS)**
- ∗ **CS-ARTILLERY (cargo-class UNITS)**
- ∗ **CS-OTHER (cargo-class UNITS)**
- ∗ **CSS-ENGINEER (cargo-class UNITS)**
- ∗ **CSS-MEDICAL (cargo-class UNITS)**
- ∗ **CSS-SIGNAL (cargo-class UNITS)**
- ∗ **CSS-SUPPORT (cargo-class UNITS)**
- ∗ **CSS-TRANSPOR (cargo-class UNITS)**
- ∗ **CSS-OTHER (cargo-class UNITS)**
- ∗ **NAVY-UE (cargo-class UNITS)**
- ∗ **RESUPPLY (cargo-class RESSUPLY)**
- ∗ **AMMUNITION (cargo-class AMMUNITION)**
- ∗ **POL (cargo-class POL)**
- ∗ **GEN-RESUPPLY (cargo-class RESSUPLY)**
- ∗ **GEN-AMMO (cargo-class AMMUNITION)**
- ∗ **GEN-POL (cargo-class POL)**

– **CARGO QUANTITY** or **CARGO DIMENSIONS:** A MOVEMENT REQUIREMENT can have a set of different categories of cargo to be moved. As this cargo would be moved by land, air, and/or sea, several different descriptions of the contents of the cargo is usually provided. These different type descriptions are needed because capacity allocation on resources obey different rules according to resource characteristics. Examples of dimensions used to describe cargo quantities are:

- ∗ **CARGO LENGTH, WIDTH** and **HEIGHT** (inches)
- ∗ **CARGO WEIGHT** (SHORT TONS)
- ∗ **CARGO CUBE** (METRIC TONS)
- ∗ **CARGO AREA** (SQUARE FEET)
- ∗ **NUMBER OF PIECES**

* **NUMBER OF PASSENGERS**
* **CARGO BULK POL** (CBBL)

5. *Additional Properties:* The MOVEMENT REQUIREMENT can also be used to specify additional classes of constraints like:
   - **SPLITTING RESTRICTIONS:** Restrictions on how the unit should be decomposed when more that one transportation resource is required.
   - **MARRY UP WINDOW:** Maximum interval of time allowed between the arrival of the first and last part of the unit to its POD or final DESTINATION.
   - **UNIT INTEGRITY:** Requirement that all parts of the unit use the same TRANSPORTATION MODE, same POE, and same POD.

5.2.4 MOVEMENT REQUIREMENT Types

Movement requirements can be classified as **PEACETIME MOVEMENT REQUIREMENTS, WARTIME and CONTINGENCY MOVEMENT REQUIREMENTS,** and **SPONSORED EXERCISES.**

During peacetime, the Military Services and the Defense Logistics Agency are responsible for the determination, collection, and submission of movement requirements for **AIRLIFT, SEALIFT,** and **CONUS CIVIL TRANSPORTATION** (Continental United States.) The categories for PEACETIME MOVEMENT REQUIREMENTS, that sometimes are also used to refer to WARTIME MOVEMENT REQUIREMENTS, are:

1. **PEACETIME MOVEMENT REQUIREMENTS**

   (a) **AIRLIFT MOVEMENT REQUIREMENTS**

      i. **CHANNEL AIRLIFT REQUIREMENT:** request for a **COMMON-USER** airlift service in a scheduled basis. When a location requires receiving service at a predetermined time, USTRANSCOM establishes a **FREQUENCY-BASED CHANNEL;** when the amount of passenger or cargo arriving at a specific port dictates a responsive scheduling of lift, USTRANSCOM establishes a **REQUIREMENTS-BASED CHANNEL.**

      ii. **SPECIAL ASSIGNMENT AIRLIFT MISSION REQUIREMENT (SAAM):** requests to satisfy unique customer requirements. These requirements may be originated by special time or geographic location conditions that precludes the use of other means of transportation.

iii. **JOINT AIRBORNE/AIR TRANSPORTABILITY TRAINING REQUIREMENT:** Request for movements to support training operations or exercises involving airborne and appropriate troop carrier units. This requests includes air delivery of personnel and equipment.

iv. **EXERCISE REQUIREMENT:** Requests to support training.

v. **COMMERCIAL DOOR TO DOOR EXPRESS REQUIREMENT:** Requests for rapid delivery of cargo.

(b) **SEALIFT MOVEMENT REQUIREMENTS**

i. **INTER-THEATER REQUIREMENT:** Movement request to move cargo between two AREAS of OPERATIONS or between CONUS and the AREA of OPERATIONS.

ii. **INTRA-THEATER REQUIREMENT:** Movement request to move cargo inside the AREA of OPERATIONS or THEATER.

iii. **COASTAL MOVEMENTS REQUIREMENT:** Request to move cargo along the continental coast.

iv. **EXERCISE REQUIREMENT:** Request to support exercises or to train personnel.

(c) **CONUS CIVIL TRANSPORTATION MOVEMENT REQUIREMENTS**

i. **RAIL TRAFFIC REQUIREMENT:** request to move cargo by railroads.

ii. **MOTOR TRAFFIC REQUIREMENT:** request to move cargo by truck or other type of wheeled vehicle.

iii. **INLAND WATERWAY TRAFFIC REQUIREMENT:** request to move cargo by waterways other than sea.

iv. **COMMAND EXPRESS SERVICE REQUIREMENT**

2. **WARTIME MOVEMENT REQUIREMENTS:** WARTIME and CONTINGENCY MOVEMENT REQUIREMENTS are established by the supported commander in coordination with supporting commanders and Military Services. There are three main types of WARTIME MOVEMENT REQUIREMENTS:

(a) **PLANNED CRISES WAR LIFT REQUIREMENTS:** There are two categories of this type of requirements:

i. **STRATEGIC DEPLOYMENT and RE-DEPLOYMENT MOVEMENT REQUIREMENTS:** The establishment and validation of DEPLOYMENT and RE-DEPLOYMENT MOVEMENT REQUIREMENTS is accomplished by developing a TPFDD in JOPES. An already existing TPFDD can be used and refined or a completely new one can be created.

ii. **SUSTAINMENT MOVEMENT REQUIREMENTS:** requirements involving the movement of replacement supplies, equipment, personnel, and units to maintain and prolong operation or combat. Sustainment requirements can be classified as

A. **CHANNEL SERVICE REQUIREMENTS**

B. **EXPRESS SERVICE REQUIREMENTS**

(b) **IN-THEATER MOVEMENT REQUIREMENTS:** The theater distribution requests include **THEATER RECEPTION REQUIREMENT** of incoming strategic cargo and request for **ONWARD MOVEMENT REQUIREMENT.** The geographic combatant commander establishes a Joint Transportation Board or a Joint Movement Center, or both and assigns one of them the responsibility for planning and coordinating all theater movement requirements. IN-THEATER MOVEMENT REQUIREMENTS can also be divided by transportation mode:

i. **SURFACE MOVEMENT REQUIREMENT.**

ii. **SEALIFT MOVEMENT REQUIREMENT.**

iii. **INLAND WATERWAY MOVEMENT REQUIREMENT.**

iv. **AIRLIFT MOVEMENT REQUIREMENT.** IN-THEATER AIRLIFT MOVEMENT REQUIREMENTS are further divided into

A. **PLANNED AIRLIFT MOVEMENT REQUIREMENTS:** when the request is known in advance,

B. **IMMEDIATE AIRLIFT MOVEMENT REQUIREMENTS:** when requirements are identified too late to the normal planning cycle.

C. **EMERGENCY MOVEMENT REQUIREMENTS:** for short notice air movement requirement.

(c) **TIME-SENSITIVE LIFT REQUIREMENTS:** these are short notice transportation requirements derived from changes in tactical situations, or other developments that may require rapid response by airlift movement. We are not including IMMEDIATE and EMERGENCY IN-THEATER AIRLIFT REQUESTS in this category. In this category we include just the strategic movements that have not been considered in the JOPES planning process. Depending on the phase of the contingency the requirement is identified, TIME-SENSITIVE MOVEMENT REQUIREMENTS can be divided into:

i. **PRE-EXECUTION TIME-SENSITIVE REQUIREMENTS** these are requirements that should be satisfied before the execution of the TPFDD starts. They are usually assigned to SAAMs.

ii. **EXECUTION TIME-SENSITIVE REQUIREMENTS** these are requirements that are identified during the deployment or operation execution phase. If USTRANSCOM lift capacity cannot be used to satisfy these requirements, alternative resources can be used or lower priority requests can be delayed.

3. **SPONSORED EXERCISES** can be classified as:

   (a) **CJCS-SPONSORED EXERCISES** (The Chairman of the Joint Chiefs of Staff.)

   (b) **CINC-SPONSORED EXERCISES** (Commander in Chief.)

Figure 5.4 summarize the different types of MOVEMENT REQUIREMENT discussed.

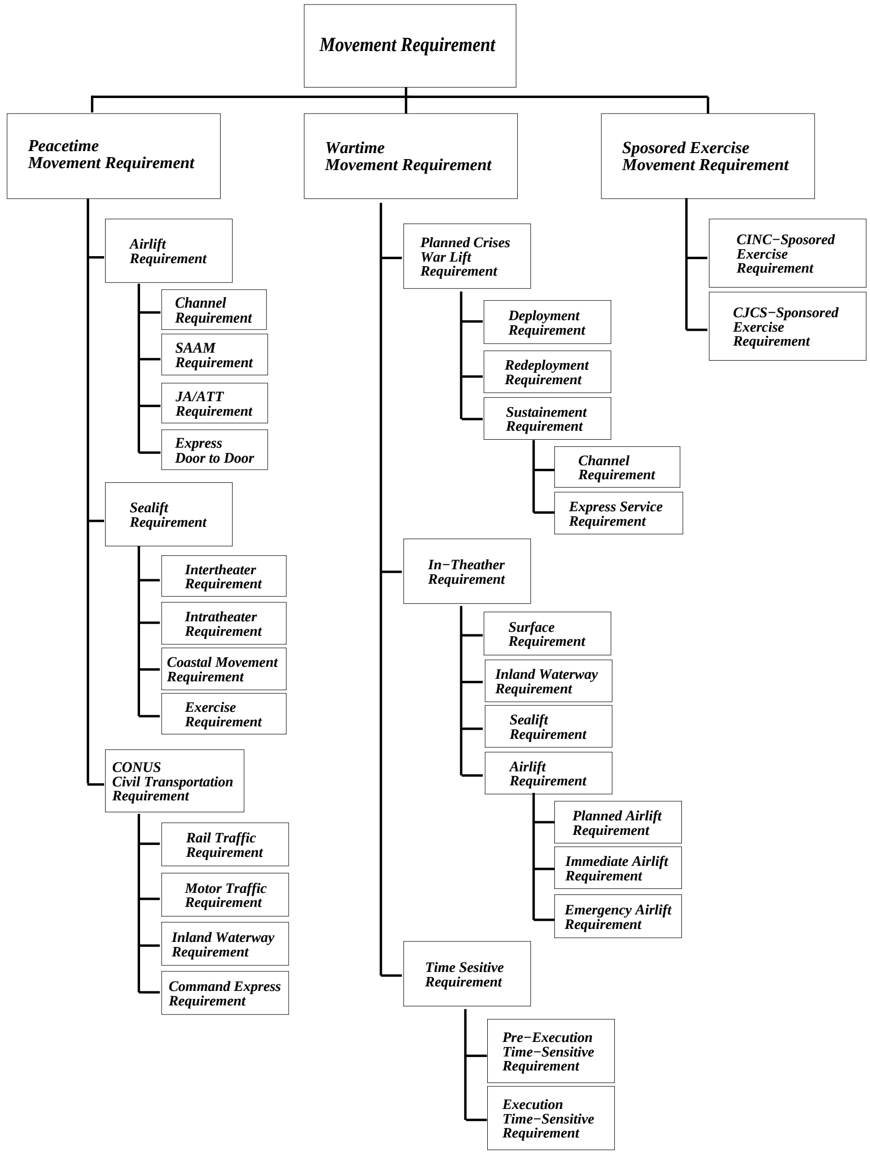

Figure 5.4: MOVEMENT REQUIREMENT Types

5.2.5 PRIORITY

A system of priority is defined for MOVEMENT REQUIREMENTS. When requirements exceed lift capacity, the requirements should be ordered by decreasing priority and higher priority requirements should be serviced first. The decreasing priority categories are[Joint-Pub-4-01, 1997]:

1. **PRIORITY 1:**

(a) **PRIORITY 1A:**

i. **PRIORITY 1A1:** A Presidentially directed mission.

ii. **PRIORITY 1A2:** US Forces and other forces in combat.

iii. **PRIORITY 1A3:** Programs approved by the President as national priority.

iv. **PRIORITY 1A4:** Special weapons.

(b) **PRIORITY 1B:**

i. **PRIORITY 1B1:** Missions directed by the Secretary of Defense.

ii. **PRIORITY 1B2:** Units, projects, or plans approved by the Secretary of Defense or by the Chairman of the Joint Chief of Staff.

iii. **PRIORITY 1B3:** Validated minimal frequency channels.

2. **PRIORITY 2:**

(a) **PRIORITY 2A:**

i. **PRIORITY 2A1:** US Forces or activities deploying or positioned and maintained is a state of readiness for immediate combat or combat support missions.

ii. **PRIORITY 2A2:** Industrial production activities engaged in repair, modification, or manufacture of primary weapons, equipments and supplies to avoid work stoppage or re-institute production.

(b) **PRIORITY 2B:**

i. **PRIORITY 2B1:** CJCS-SPONSORED EXERCISES.

ii. **PRIORITY 2B2:** CINC-SPONSORED EXERCISES.

3. **PRIORITY 3:**

(a) **PRIORITY 3A:**

i. **PRIORITY 3A1:** Readiness or evaluation test when airlift is required in support of unit inspection or evaluation tests.

ii. **PRIORITY 3A2:** US Forces or activities maintened in a state of readiness to deploy for combat or combat support activities.

iii. **PRIORITY 3A3:** Approved requirement channels.

(b) **PRIORITY 3B:**

i. **PRIORITY 3B1:** Support JOINT AIRBORNE / AIR TRANSPORTABILITY TRAINING when airborne operations or airlift support is integral to combat readiness.

ii. **PRIORITY 3B2:** Combat support training.

iii. **PRIORITY 3B3:** Service schools requiring airborne, airdrop, or air transportability as part of the instruction program.

iv. **PRIORITY 3B4:** Airdrop / air transportability or aircraft certification of new or modified equipment.

4. **PRIORITY 4:**

   (a) **PRIORITY 4A:**

      i. **PRIORITY 4A1:** US forces or activities employed in support of approved war plans.
      ii. **PRIORITY 4A2:** Static loading exercises for units that should perform air transportability missions.

   (b) **PRIORITY 4B:**

      i. **PRIORITY 4B1:** Other US forces and activities.
      ii. **PRIORITY 4B2:** Non DOD-activities that cannot use commercial means of transportation.
      iii. **PRIORITY 4B3:** Static display for military or public events.

5.3 PRODUCTS or DEMAND OBJECTIVES

5.3.1 Concept Definition.

A **PRODUCT** is a generic type of good or service provided by some system of interest. A PART-TYPE is a typical PRODUCT of a manufacturing system; a transportation system alternatively provides TRANSPORT-SERVICES. A PRODUCT is realized through execution of some set of ACTIVITIES. A DEMAND for a PRODUCT is considered satisfied when all of these ACTIVITIES have completed. More generically, the PRODUCT can be considered the goal or objective to be satisfied. In this sense, we also refer to the PRODUCT as the DEMAND OBJECTIVE. Figure 5.5 shows the dependency between the PRODUCT and the DEMAND.

Although the PRODUCT is usually seen as the output of the ACTIVITIES, in the OZONE ontology it has a different meaning. The PRODUCT is the entity that encodes the knowledge about the system capabilities. The fact that there is a TRANSPORT-SERVICE available in the system, means that the scheduler system knows about the set of ACTIVITIES and corresponding RESOURCES required to provide this service. If a DEMAND requesting this kind of service is introduced into the system, it is the PRODUCT responsibility to generate a set of RESOURCE requirements and a set of constraints on the utilization of these resources such that the DEMAND can be satisfied. These constrained resource requirements are the ACTIVITIES that, when executed, will satisfy the requirements specified in the DEMAND.

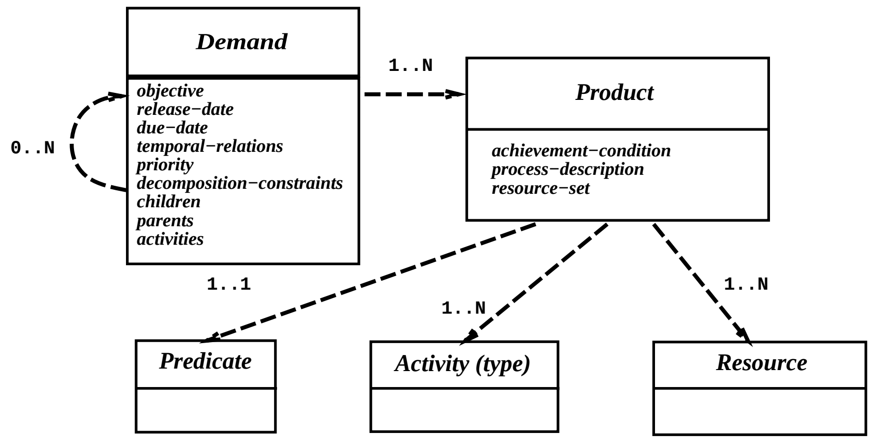

Figure 5.5: Product Structure

5.3.2 Properties

From the standpoint of managing system ACTIVITIES in response to external DEMANDS, properties of interest in defining a PRODUCT relate to the mapping from DEMANDS to ACTIVITIES. Specifically, a PRODUCT definition includes the following:

- **ACHIEVEMENT CONDITION:** this corresponds to the goal specified by the DEMAND. It is the desired state to be achieved by the execution of a sequence of ACTIVITIES. For example, if a manufacturing order requests a certain number of parts to be delivered at a certain date, the ACHIEVEMENT CONDITION would be that a predicate like *READY-ON-TIME (part-type, quantity, scheduled-end-time)* evaluates to true. This is equivalent to say that the actual production system has produced the quantity of parts specified in the DEMAND before its DUE-DATE.

  In the transportation domain, the ACHIEVEMENT CONDITION would be that all the cargo specified in the MOVEMENT REQUIREMENT is at the DESTINATION at no later time than its REQUIRED DELIVERY DATE. Satisfying this condition is equivalent to satisfying the DEMAND.

- **PROCESS DESCRIPTION** - the set of processing steps required to produce or provide the PRODUCT (i.e., a plan for realizing this PRODUCT.) A PRODUCT specification, together with the constraints and parameters of a requesting DEMAND, enables instantiation of a set of ACTIVITIES for fulfilling the DEMAND (*Instantiate-Product-Plan*). From a scheduling perspective, these ACTIVITIES contain the decision variables (start times, end times, assigned resources) of the problem to be solved; and the instantiation process restricts the domains of these decision variables according to the constraints specified in the DEMAND.

In the same way a PRODUCT corresponds to the notional service capability provided by the system, the PROCESS DESCRIPTION corresponds to the notional sequence of ACTIVITIES required to satisfy the ACHIEVEMENT CONDITION. The PROCESS DESCRIPTION can be a plan template that gets instantiated, or a set of procedures that gets executed to generate the actual sequence of required ACTIVITIES. For example, depending on the weather conditions and status of the Panama and Suez channel, different sets of ROUTES and ITINERARIES would be selected and different sets of ACTIVITIES would then be generated.

- **RESOURCES** - the set of resources that can be utilized to execute various ACTIVITIES of the PRODUCT plan. To instantiate an actual set of ACTIVITIES from the notional PROCESS DESCRIPTION, the PRODUCT needs knowledge about RESOURCE availability and capability. The knowledge about RESOURCES can be embedded in the PROCESS DESCRIPTION or can be made explicit in the PRODUCT representation. Figure 5.6 shows an example of two alternative representations. The MOVEMENT REQUIREMENT specifies a certain amount of OUTSIZE cargo to be moved. OUTSIZE cargo can only be transported in C5s. On the left side of figure 5.6 the OUTSIZE MOVEMENT product has a generic TRANSPORT ACTIVITY as its PROCESS DESCRIPTION and the set of available C5s as its RESOURCES. The instantiation of the PROCESS DESCRIPTION involves adding the resources specified in the PRODUCT to the ACTIVITY instance. On the right side, the PROCESS DESCRIPTION is an OUTSIZE TRANSPORT ACTIVITY type. This activity type already has the set of C5s as its set of ALTERNATIVE RESOURCES. When an instance of the OUTSIZE TRANSPORT ACTIVITY is created, the set of C5s is already in place and the information in the PRODUCT is irrelevant.

5.3.3 TRANSPORT SERVICES

The PRODUCT of a TRANSPORTATION SYSTEM is a TRANSPORT SERVICE. The set of TRANSPORT SERVICES available defines the capabilities of the MILITARY TRANSPORTATION SYSTEM being modeled. In section 5.2.4 we have presented the different types of MOVEMENT REQUIREMENTS. The same classification used for MOVEMENT REQUIREMENTS can be used for TRANSPORT SERVICES since one can assume that each type of requirement should be satisfied by a special type of transportation service. A PEACETIME SEALIFT MOVEMENT REQUIREMENT would be satisfied by a PEACETIME SEA TRANSPORT SERVICE. If PEACETIME and WARTIME transportation procedures are

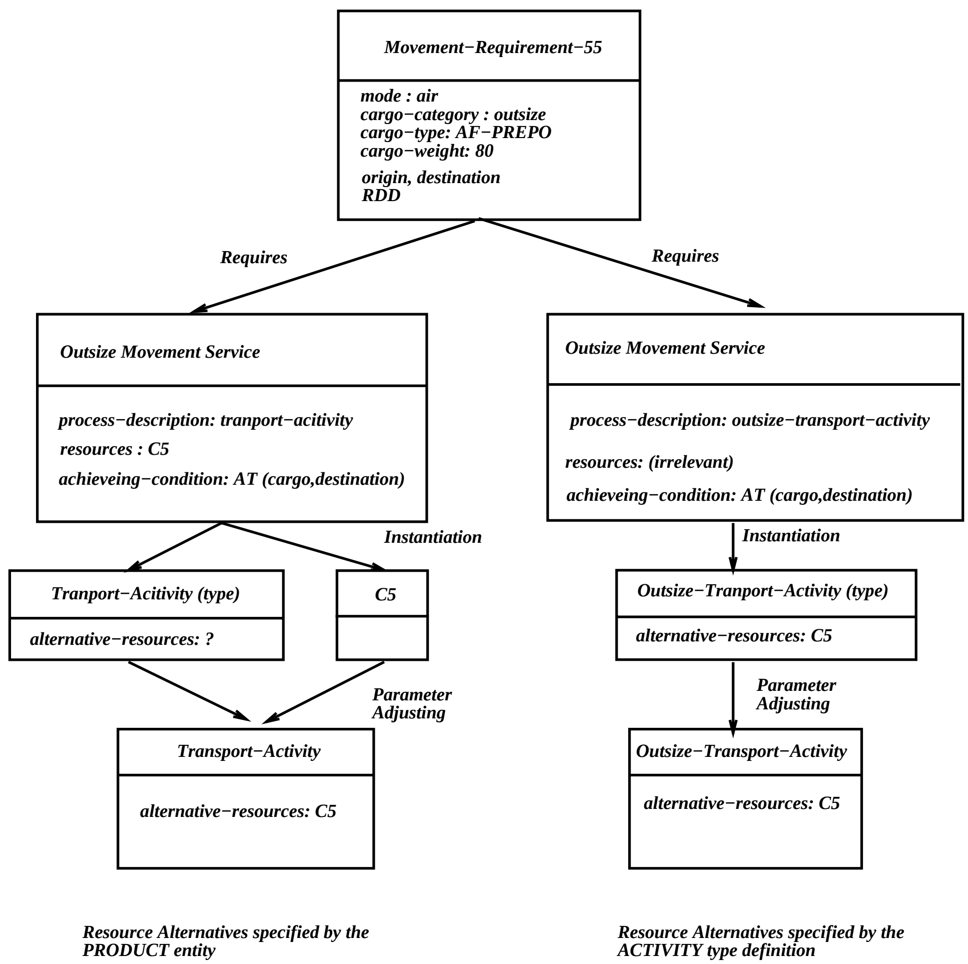

Figure 5.6: Alternative PRODUCT Representations

similar or equal, a SEA TRANSPORT SERVICE would satisfy both a PEACE-TIME and a WARTIME SEALIFT REQUIREMENT. The decision of specializing or not the TRANSPORT SERVICE is a function of the LEVEL OF DETAIL and LEVEL OF SPECIFICATION of the representation.

The TRANSPORT SERVICE is the entity that encodes the knowledge necessary to create the set of transportation ACTIVITIES that would satisfy the MOVEMENT REQUIREMENT. Figure 5.7 shows a summarized representation of the structure of the TRANSPORT SERVICE entity. We can roughly divide the class of TRANSPORT SERVICES in four groups:

1. **SEA TRANSPORT SERVICE:** During large strategic deployment, sealift support is typically conducted in three phases. We use these phases to characterize the different types of SEA TRANSPORT SERVICE:

(a) **PREPOSITIONING:** When cargo is moved to strategic positions in support of rapid deployment requirements of various services. These services are usually provided by the AFLOAT-PREPOSITIONING FORCE and MARITIME PRE-POSITIONING SHIPS (see section 5.4.4.) Two types of PREPOSITIONING services are identified:

   i. **ASHORE PREPOSITIONING**

   ii. **AFLOAT PREPOSITIONING**

(b) **SURGE SEA TRANSPORT SERVICE:** Service provided by the USTRANSCOM controlled fleet to deliver heavy combat power and accompanying supplies to facilitate deployment of CONUS based forces to anywhere in the world.

(c) **SUSTAINMENT SEA TRANSPORT SERVICE:** Service provided by the US Merchant Fleet to deliver large quantities of ammunition and resupply to forward-deployed forces. If necessary, the READY RESERVE FLEET is also used (see section 5.4.4.)

An additional type of SEA TRANSPORT SERVICE is the support of amphibious operations. We designate these services as **AMPHIBIOUS OPERATION SERVICES.**

2. **AIR TRANSPORT SERVICES:** the types of airlift provided are related to the type of requests and have already been discussed in section 5.2.4. The basic types of AIR TRANSPORT SERVICES are:

   (a) **CHANNEL SERVICE**

   (b) **SAAM SERVICE**

   (c) **JA/ATT SERVICE**

   (d) **EXPRESS AIR SERVICE**

   (e) **AERO-MEDICAL-EVACUATION SERVICE**

   (f) **EXERCISE SERVICE**

3. **INLAND OR GROUND TRANSPORT SERVICES:** These services are classified according to the type of transportation resource used:

   (a) **INLAND TRACK SERVICE**

   (b) **INLAND MOTOR SERVICE**

   (c) **INLAND WATERWAY SERVICE**

   (d) **EXPRESS INLAND SERVICE**

4. **MULTI-MODE TRANSPORT SERVICES:** these services involves a combination of SEA, LAND, and/or AIR TRANSPORT SERVICES to satisfy the requirement.

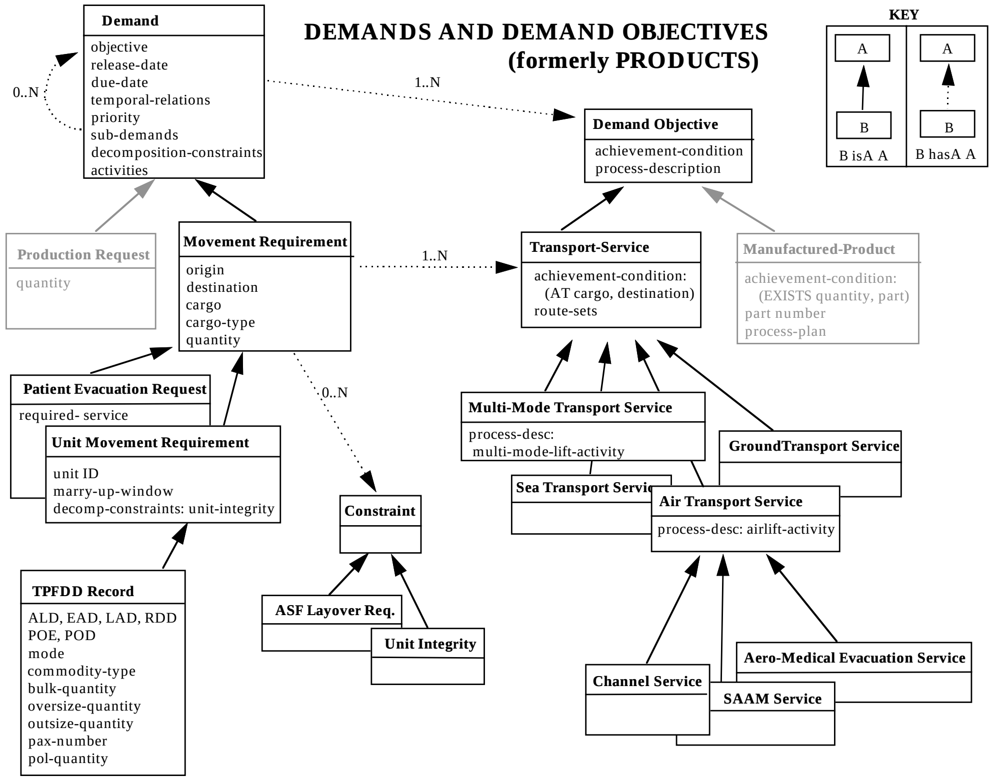

Figure 5.7: TRANSPORT SERVICES

Additional properties can be defined for TRANSPORT SERVICE. In the example of figure 5.7, the set of available routes has been added as a property of the service being provided.

5.4 RESOURCES

5.4.1 Concept Definition

Central to the definition of our scheduling ontology is the concept of a RESOURCE. A **RESOURCE** is an entity that supports or enables the execution of ACTIVITIES. RESOURCES are generally in finite supply and their availability constrains when and how ACTIVITIES execute. Making efficient use of RESOURCES in support of multiple, competing ACTIVITIES is the crux of the scheduling problem, and, from the standpoint of constructing scheduling models, the distinguishing characteristics of RESOURCES relate to constraints on their availability. Figure 5.8 provides an overview of the different RESOURCE

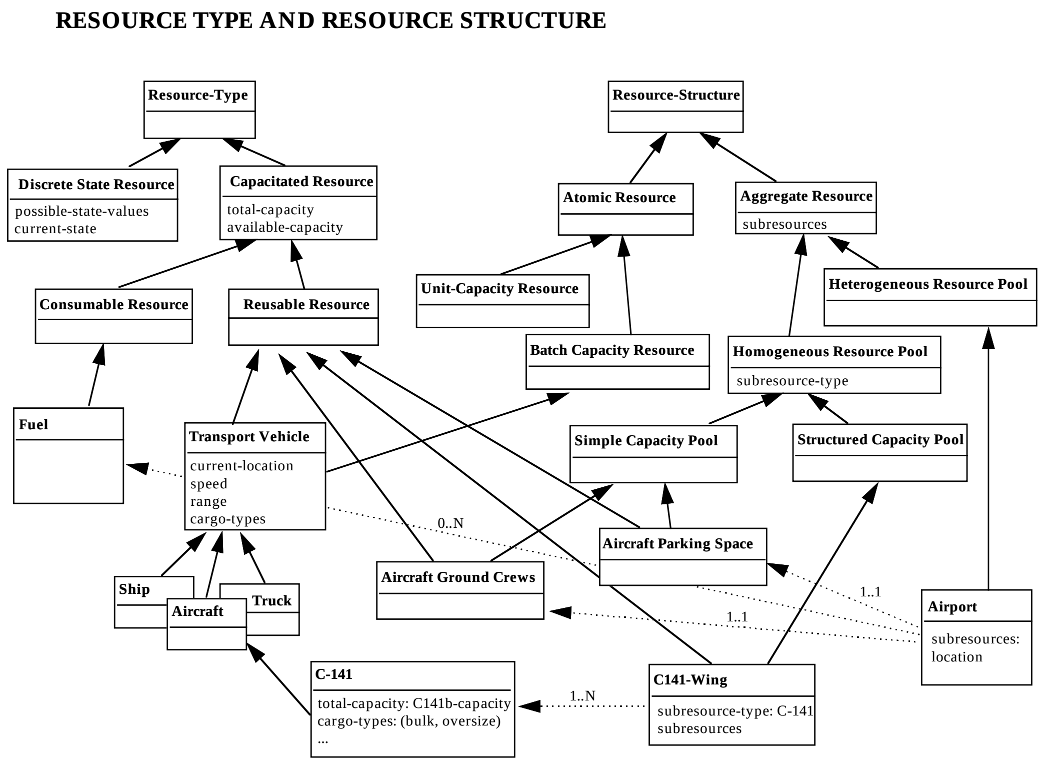

Figure 5.8: RESOURCE Structure

types modeled in the OZONE ontology.

The availability of a RESOURCE can be defined generally in terms of some dynamically changing aspect of state. Most typically, a RESOURCE is modeled as providing some amount of CAPACITY, a numeric quantity which varies over time as a function of allocating the RESOURCE to various ACTIVITIES and its associated allocation semantics. This is the approach taken in [Fadel, M.S. Fox, & Gruninger, 1994, Uschold *et al.*, 1996]. However, there are also RESOURCES whose availability is more a function of qualitative state: ACTIVITIES require the RESOURCE to be in a particular state or subset of possible states (e.g., to be *idle* as opposed to *busy*) rather than requiring that the RESOURCE have a sufficient amount of CAPACITY. Hence we distinguish two broad classes of resources from the standpoint of availability:

1. **DISCRETE-STATE RESOURCES:** RESOURCES whose availability is a function of some discrete set of possible state values. Here definitions provide analogous capabilities for querying, updating and protecting state values over time.

2. **CAPACITATED RESOURCES:** RESOURCES whose availability is char-

acterized in terms of the amount of CAPACITY that is available. In this case, concept specializations provide capabilities for maintaining a representation of available capacity over time (*Increase-Capacity, Decrease-Capacity*), for allocating and deallocating capacity to activities (*Allocate-Capacity, DeAllocate-Capacity*), and for finding periods where capacity is available (*Find-Available-Time*).

In the case of CAPACITATED-RESOURCES, constraints on availability (i.e. usage of capacity) depend on several different properties of the resource. One determining characteristic is whether RESOURCE CAPACITY is used or consumed by an ACTIVITY when it is allocated:

(a) A **REUSABLE RESOURCE,** is a RESOURCE whose capacity becomes available for reuse after an ACTIVITY to which it has been allocated finishes. We say that the ACTIVITY uses the RESOURCE[Uschold *et al.*, 1996]

(b) A **CONSUMABLE RESOURCE,** is one whose CAPACITY, once allocated to an ACTIVITY does not become available again. We say that the ACTIVITY consumes the RESOURCE.

Though we could further distinguish a third class,*RENEWABLE RESOURCES*, to refer to RESOURCES that have their CAPACITY increased by ACTIVITIES [Fadel, M.S. Fox, & Gruninger, 1994], we instead consider production of RESOURCE CAPACITY to be a separable issue. In our model, ACTIVITIES utilize RESOURCES to produce PRODUCTS. In a resource producing ACTIVITY, the RESOURCE CAPACITY generated is the PRODUCT (or output) of the ACTIVITY; it is not assuming the role of a RESOURCE in this context. Moreover, RENEWABILITY is a property that is equally relevant to REUSABLE-RESOURCES as well as CONSUMABLES. Any RESOURCE can be designated as RENEWABLE by additionally defining it to be a PRODUCT.

A second aspect of RESOURCES that impacts usage (or consumption) of CAPACITY by ACTIVITIES is physical structure. In this respect, RESOURCES can be classified as:

1. **ATOMIC RESOURCE:** This is a RESOURCE that is not divisible and can only be configured to support one process at a time. We can distinguish two subtypes:

   (a) A **UNIT-CAPACITY RESOURCE** can only be used by one ACTIVITY during any given TIME-INTERVAL. In this case we could equivalently model the RESOURCE as a discrete state variable with two values : *busy* and *idle*.

(b) A **BATCH-CAPACITY RESOURCE** can support multiple ACTIVITIES if there is sufficient capacity, and if they require the same resource configuration and are temporally synchronized to occur over the same TIME-INTERVAL. BATCHING COMPATIBILITY constraints specify the commonality in resource configuration that is required of multiple ACTIVITIES for simultaneous use of a BATCH-CAPACITY-RESOURCE. These constraints are defined with respect to different types of ACTIVITIES that the RESOURCE can support. For example, for two TRANSPORT-ACTIVITIES to be supported by the same vehicle at the same time, both have to require transport between the same locations.

2. An **AGGREGATE RESOURCE** represents a pool of resources, which may be composed of smaller AGGREGATE RESOURCES or ATOMIC RESOURCES. The CAPACITY of an AGGREGATE RESOURCE reflects the collective CAPACITY of its constituent SUB-RESOURCES. This CAPACITY can be independently allocated to multiple activities over any given TIME-INTERVAL, subject only to any constraints induced from the structure of the aggregated SUB-RESOURCES. Based on the nature of SUB-RESOURCE structure, we can define several types of AGGREGATE RESOURCE:

   (a) **HOMOGENEOUS RESOURCE POOL:** An AGGREGATE RESOURCE composed of n SUB-RESOURCES of the same type. HOMOGENEOUS RESOURCE-POOLS can be further differentiated as:

      i. **SIMPLE-CAPACITY POOL:** A HOMOGENEOUS RESOURCE POOL which is composed of n UNIT-CAPACITY-RESOURCES and can thus simultaneously support n independent activities. This corresponds to the definition of CAPACITATED RESOURCE given in [Fadel, M.S. Fox, & Gruninger, 1994].

      ii. **STRUCTURED-CAPACITY POOL:** A HOMOGENEOUS RESOURCE POOL composed of n BATCH-CAPACITY RESOURCES or n AGGREGATE RESOURCES of capacity c, having total CAPACITY $n * c$. This type of resource can simultaneously support n independent activities only if the capacity required by any one activity $\leq c$. Any extra capacity over a given TIME-INTERVAL can potentially be used to support additional activities, but only if COMPATIBILITY constraints are satisfied.

   (b) **HETEROGENEOUS RESOURCE POOL:** An AGGREGATE RESOURCE that is composed of RESOURCES of different types and CAPACITIES.

Regardless of the level of detail at which RESOURCE allocation decisions are to be considered in a given domain (e.g., at the level of ATOMIC

RESOURCES or higher), AGGREGATE RESOURCES capture the hierarchical structure of domain resources in most environments. One consequence is that the unavailability of an AGGREGATE RESOURCE over a given TIME-INTERVAL always implies the unavailability of its constituent SUB-RESOURCES over the same TIME-INTERVAL.

5.4.2 Properties

The properties of a RESOURCE of primary interest here are those which affect its availability and utilization. Lets first consider availability. In the case of a CAPACITATED RESOURCE, availability is a function of its **CAPACITY**. CAPACITY is a QUANTITY (or set of QUANTITIES) of some unit measure (e.g., volume, weight, number of activities) that is available for allocation to ACTIVITIES over time. The allocation of a CAPACITATED RESOURCE to an ACTIVITY implies use or consumption of some amount of CAPACITY, and the number of ACTIVITIES that can be simultaneously supported is limited by the total CAPACITY of the RESOURCE. We can distinguish between different types of CAPACITY models, which impose different CAPACITY CONSTRAINTS.

Figure 5.9 shows the different CAPACITY models and some examples of RESOURCE representations that use these models:

- A **UNIFORM-CAPACITY** model represents CAPACITY as a scalar QUANTITY. The CAPACITY-CONSTRAINT of a RESOURCE with UNIFORM-CAPACITY requires that, at any point in time, the sum of the CAPACITY used/consumed by all supported ACTIVITIES $\leq$ the CAPACITY of the RESOURCE.
- A **HETEROGENEOUS-CAPACITY** model represents CAPACITY as a vector of two or more UNIFORM-CAPACITIES, reflecting partitioned sub-CAPACITIES. For example, a ship might have separate cargo holds. The CAPACITY-CONSTRAINT of a RESOURCE with HETEROGENEOUS-CAPACITY is the conjunction of the CAPACITY-CONSTRAINTS associated with constituent UNIFORM-CAPACITIES.
- A **MULTI-DIMENSIONAL-CAPACITY** model defines CAPACITY in terms of two or more QUANTITIES, with each contributing a separate CAPACITY CONSTRAINT that must be satisfied. For example, the capacity of an aircraft might be defined in terms of both maximum weight and volume. In the case of MULTI-DIMENSIONAL-CAPACITY, the CAPACITY-CONSTRAINT requires that for each different unit measure, the sum of the CAPACITY utilized by all supported ACTIVITIES $\leq$ the CAPACITY of the RESOURCE.

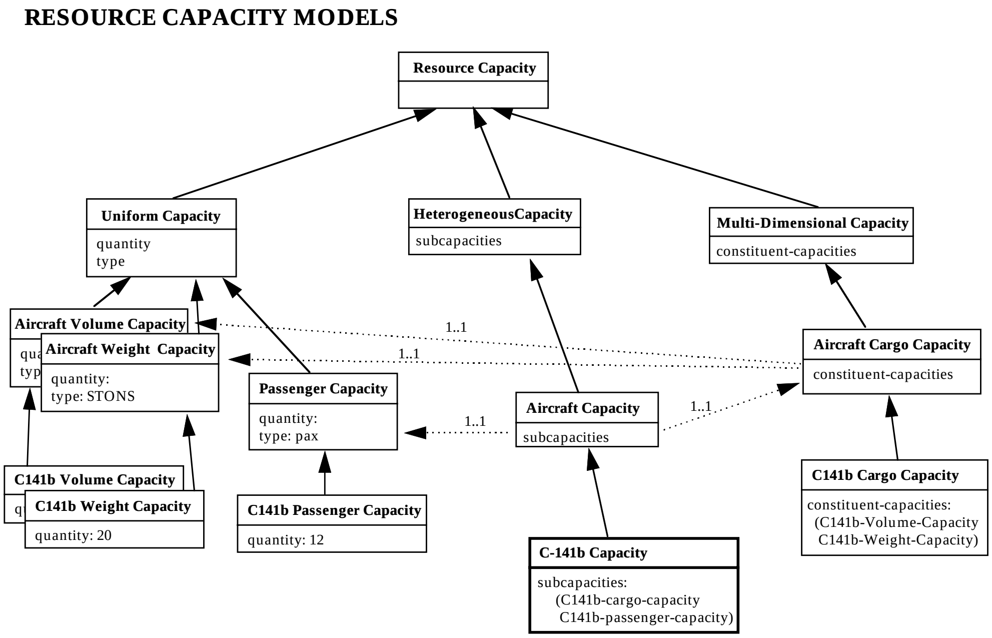

Figure 5.9: RESOURCE Capacity Models

In the case of a DISCRETE-STATE-RESOURCE, “availability” corresponds to being in a state that matches the condition of the ACTIVITY that requires the resource. A DISCRETE-STATE-RESOURCE has a set of possible STATE-VALUES. If the RESOURCE is controllable, individual STATE-VALUES can be additionally defined as PRODUCTS; this allows linkage to ACTIVITIES for bringing about their specific values. Allocation of a DISCRETE-STATE-RESOURCE to an ACTIVITY implies commitment to (or protection of) a specific STATE-VALUE over some TIME-INTERVAL, and multiple ACTIVITIES can be simultaneously supported, as long as compatible STATE-VALUES are required.

In many cases, usage of a RESOURCE also depends on other physical properties. Generally, the physical properties of interest will be a function of the domain, but some fairly generic examples include its **SPEED**, which constrains how long ACTIVITIES take to perform, and its **RANGE**, which affects whether it can be used for a particular ACTIVITY or not. Another general physical property of a REUSABLE-RESOURCE is its **SETUP-DURATION**, which specifies how long it takes to configure the RESOURCE for use by a particular ACTIVITY. We can distinguish different types of SETUP-DURATION models:

- A **CONSTANT-SETUP-TIME** model implies that the RESOURCE requires a fixed amount of time to be configured for use by an ACTIVITY, regardless of its prior state.
- A **STATE-DEPENDENT-SETUP-TIME** model implies that the amount of time required to configure the RESOURCE for use by an ACTIVITY is variable and depends on the specific prior configuration of the RESOURCE. A special form of STATE-DEPENDENT-SETUP-TIME is **SEQUENCE-DEPENDENT-SETUP-TIME**, where setup time is assumed to be a function of the last ACTIVITY that was processed using the RESOURCE.

Other **USAGE-RESTRICTIONS** can also limit the availability of RESOURCES:

- **UNAVAILABILITY-INTERVALS** - A TIME-INTERVAL where a RESOURCE cannot be allocated is one simple type of USAGE-RESTRICTION. UNAVAILABILITY INTERVALS can reflect **RESOURCE-BREAKDOWNS**, periods where **DOWN-SHIFTS** or **RESOURCE-MAINTENANCE** have been planned, or other unmodeled circumstances.
- **CUMULATIVE-USAGE-CONSTRAINTS** - There may also be restrictions on the total amount of RESOURCE use permitted over a given TIME-INTERVAL.

5.4.3 TRANSPORTATION RESOURCES

In the previous subsections, we have classified RESOURCES according to their physical structure and related CAPACITY models. In the transportation domain, however, it makes more sense to classify them according to functionality and type of service provided. This division is also related to the management of RESOURCES and responsibilities for the execution of the associated ACTIVITIES We consider three broad categories of RESOURCES: **TRANSPORT RESOURCES, TRANSPORT TERMINALS,** and **AUXILIARY RESOURCES.** These categories are further specialized according to other characteristics:

1. **TRANSPORT RESOURCES:** this term refers to RESOURCES capable of moving between two different geographic LOCATIONS. TRANSPORT RESOURCES are classified according to two dimensions. The first dimension is the MODE OF TRANSPORTATION. The MODE OF TRANSPORTATION defines the managing organization, the type of TERMINALS that can be used, and the characteristics of cargo that can be transported. The RESOURCE types according to TRANSPORTATION MODE are:

   (a) **AIR RESOURCES**

(b) **SEA RESOURCES**

(c) **SURFACE RESOURCES**

The second dimension is the level of aggregation:

(a) **TRANSPORT VEHICLE:** The ATOMIC RESOURCE capable of moving the entire cargo from an ORIGIN to a DESTINATION during the same TIME-INTERVAL. The VEHICLE is treated as a unit by the scheduler. Individual aircraft, ships, and trucks are examples of VEHICLES. Additional properties of TRANSPORT VEHICLES are:

- **VELOCITY:** The maximum or average speed the RESOURCE can travel.
- **RANGE:** the maximum or average distance the RESOURCE can travel.
- **LOCATION:** a state variable that keeps track of the RESOURCE position over time

TRANSPORT VEHICLES are, in general, a more specialized type of ATOMIC RESOURCE, they are BATCH CAPACITY RESOURCES. Although certain VEHICLES could behave as a UNIT CAPACITY RESOURCE, a TRANSPORT VEHICLE is usually capable of transporting more than one piece of cargo in the same trip. The trip defines the batch and all the pieces that can use this trip and would still fit into the VEHICLE establish the cargo of the batch.

(b) **TRANSPORT FLEET:** VEHICLES are aggregated into FLEETS. Two types of FLEET are considered:

i. **HOMOGENEOUS FLEET:** An HOMOGENEOUS RESOURCE POOL. All the SUB-RESOURCES of an HOMOGENEOUS FLEET are of the same type. For example, a C141-Fleet is a fleet composed only of C141s.

ii. **HETEROGENEOUS FLEET:** An HETEROGENEOUS RESOURCE POOL. The SUB-RESOURCES of an HETEROGENEOUS POOL can be of different types. For example, the AMC-PLANE-FLEET has RESOURCES of type C5, C141, C130, etc.

By combining the two dimensions, additional RESOURCE types can be defined. For example, an AIRLIFT is an AIR RESOURCE and a VEHICLE; and a C5 FLEET is an AIR RESOURCE and an HOMOGENEOUS FLEET. AIRLIFT and SEALIFT RESOURCE are discussed in more details in section 5.4.4 and 5.4.4 respectively.

2. **TRANSPORT TERMINALS:** geographic LOCATIONS equipped with facilities capable of on-loading and offloading TRANSPORT RESOURCES. Geographic **LOCATIONS** are characterized by its name, LATITUDE,

LONGITUDE, and GEOLOCATION CODE, a four character, alphanumeric code that uniquely identifies the LOCATION. Two types of TRANSPORT TERMINALS are modeled:

(a) **SEAPORT** or just **PORTS**

(b) **AERIAL PORTS** or **AIRPORTS**

The term PORT should not be used in conjunction with air facilities[Joint-Pub-1-02, 1994] TERMINAL capacity is discussed in more details in section 5.4.5.

3. **AUXILIARY RESOURCES:** secondary RESOURCES needed to support TERMINAL operations and TRANSPORT ACTIVITIES. Examples of these types of RESOURCES are equipment to on/offload cargo, pallets, containers, forklifts, ground crews. These RESOURCES are considered secondary from a scheduling perspective. By this we mean that the scheduler will verify AUXILIARY RESOURCE availability if required by the level of detail of the model, but will not reason about the best RESOURCE available to process the AUXILIARY ACTIVITIES. AUXILIARY RESOURCES and associated ACTIVITIES can be promoted to TRANSPORT RESOURCES and TRANSPORT ACTIVITIES, or whatever type they correspond to, if required.

5.4.4 LIFT RESOURCES

The CAPACITY models for AIRLIFTS and SEALIFTS is relatively complex. This complexity is mainly due to the number of possible interactions among different types of cargo. Besides these interactions, the AVAILABLE CAPACITY of certain RESOURCES is function of several different dimensions. For example, the available CAPACITY of a given RESOURCE could be described in terms of weight and height. A certain piece of cargo would be transported by this resource if its weight and height does not exceed the maximum weight and height specified by the RESOURCE. Both conditions have to be satisfied. If the conditions are satisfied and the cargo gets scheduled in the RESOURCE, the RESOURCE AVAILABLE CAPACITY needs to be updated to reflect the reservation. In certain cases both dimensions are affected, in other cases only one of them is affected.

To deal with these kind of situations, we have defined the CAPACITY MODELS described in section 5.4.2 and represented in figure 5.9.

AIRLIFT and SEALIFT have slightly different CAPACITY MODELS.

AIRLIFT CAPACITY

AIRLIFT CAPACITY is modeled as an HETEROGENEOUS CAPACITY RESOURCE. AIRLIFTS are represented as having two different **CARGO HOLDERS.** One of the CARGO HOLDERS, the PASSENGER CABIN, behave as a UNIFORM CAPACITY RESOURCE. The TOTAL CAPACITY of the PASSENGER CABIN represents the maximum number of passengers that can fly at any given time in the aircraft. As a trip is established, reservations for passengers just decrease the number of available seats. The second CARGO HOLDER is for cargo and is independent of the passenger capacity. The AIRLIFT cargo AVAILABLE CAPACITY is a function of the CARGO TYPE and CARGO CATEGORY specified in the MOVEMENT REQUIREMENT. AIRLIFT CARGO TYPES are BULK, OVERSIZE and OUTSIZE. These types roughly describes the physical dimensions, other than weight, of the unit to be moved. The dimensions of these types of cargo is provided in section 5.2.3. For each CARGO CATEGORY (see section 5.2.3) the AIRLIFT CAPACITY is expressed in term of maximum weight (SHORT TONS) of BULK, or **BULK-PAYLOAD**; maximum weight (SHORT TONS) of OVERSIZE, or **OVERSIZE-PAYLOAD**; maximum weight (SHORT TONS) of OUTSIZE cargo, or **OUTSIZE PAYLOAD** that can be transported. These three dimensions are not independent. They are affected depending of the type and quantity of cargo that gets assigned to the RESOURCE:

1. BULK cargo up to a certain amount does not affect OVERSIZE and OUTSIZE availability. Above this certain amount, it affects both.
2. OVERSIZE cargo always affects BULK capacity and up to a certain value does not affect OUTSIZE capacity.
3. OUTSIZE cargo always affect BULK and OVERSIZE capacity.
4. The maximum values are different for different CARGO CATEGORIES.
5. Using the same AIRLIFT for different types of CARGO CATEGORIES adds extra complexity to the model.

Not all RESOURCES can carry all types of cargo. Certain AIRLIFTS can carry only passengers, others can carry certain types of cargo and passengers, others can carry only certain types of cargo and no passengers. Some examples of AIRLIFT types and respective PAYLOADS for some of the CARGO CATEGORIES are:

- **C-5A:**
  1. **PAX-PAYLOAD**
     - **AF-AIRCRAFT:** 97

- **AF-SUPPORT:** 94
    - **AMMUNITION:** 0

  2. **BULK-PAYLOAD**
     - **AF-AIRCRAFT:** 68.4
     - **AF-SUPPORT:** 68.4
     - **AMMUNITION:** 89.1

  3. **OVERSIZE-PAYLOAD**
     - **AF-AIRCRAFT:** 52.4
     - **AF-SUPPORT:** 68.4
     - **AMMUNITION:** 0.0

  4. **OUTSIZE-PAYLOAD**
     - **AF-AIRCRAFT:** 90.6
     - **AF-SUPPORT:** 75.2
     - **AMMUNITION:** 0.0

- **C-141B:**

  1. **PAX-PAYLOAD**
     - **AF-AIRCRAFT:** 34
     - **AF-SUPPORT:** 40
     - **AMMUNITION:** 0

  2. **BULK-PAYLOAD**
     - **AF-AIRCRAFT:** 24.7
     - **AF-SUPPORT:** 24.7
     - **AMMUNITION:** 29.7

  3. **OVERSIZE-PAYLOAD**
     - **AF-AIRCRAFT:** 14.4
     - **AF-SUPPORT:** 22.9
     - **AMMUNITION:** 0.0

  4. **OUTSIZE-PAYLOAD**
     - **AF-AIRCRAFT:** 0.0
     - **AF-SUPPORT:** 0.0
     - **AMMUNITION:** 0.0

- **B-747P:**

  1. **PAX-PAYLOAD**
     - **AF-AIRCRAFT:** 401

- **AF-SUPPORT:** 401
- **AMMUNITION:** 401

2. **BULK-PAYLOAD**
   - **AF-AIRCRAFT:** 0.0
   - **AF-SUPPORT:** 0.0
   - **AMMUNITION:** 0.0
3. **OVERSIZE-PAYLOAD**
   - **AF-AIRCRAFT:** 0.0
   - **AF-SUPPORT:** 0.0
   - **AMMUNITION:** 0.0
4. **OUTSIZE-PAYLOAD**
   - **AF-AIRCRAFT:** 0.0
   - **AF-SUPPORT:** 0.0
   - **AMMUNITION:** 0.0

SEALIFT RESOURCES

SEALIFT CAPACITY is also modeled as an HETEROGENEOUS CAPACITY RESOURCE. A SEALIFT can have up to three different CARGO HOLDERS. One cargo holder has AVAILABLE CAPACITY expressed in terms of available VOLUME. This capacity is called the **BALE CUBIC** and corresponds to the internal volume of the bellow-deck cargo compartments available for general or "package" cargo. It is expressed either in cubic feet (ft3) or in measurement tons (MTs) of 40 ft3 per ton.

The second CARGO HOLDER has its capacity expressed in terms of AREA. This capacity is called the **SQUARE FOOTAGE** and corresponds to the total deck areas, expressed in square feet, considered usable for stowage of cargo

The third third has its capacity expressed in terms of **CONTAINERS** and is described in terms of number of 20-feet containers it can hold. Containerized cargo can also be loaded by volume since it is easy to estimate the volume occupied by the container box. Similarly, the container cargo holder can also be loaded by volume.

Ships capable of transporting liquid cargo have their capacity described in terms of standard barrels (BBLs) of 42 US gallons. This volume corresponds to the total internal volume of ship's liquid cargo tanks.

Another measurement of ship capacity is the **CARGO DEADWEIGHT** that is the weight of the cargo that the ship can carry when fully crewed, fueled, and provisioned. It is measure in LONG TONS (LTs) of 2,240 pounds.

The available capacity is a function of the CARGO CLASS (SPECIAL, UNITS, RESUPPLY, AMMUNITION, POL) and CARGO CATEGORY (CONTAINERIZABLE, WHEELED EQUIPMENT, TRACKED EQUIPMENT, AVIATION EQUIPMENT, NON-CONTAINERIZABLE NON-VEHICULAR) specified in the MOVEMENT REQUIREMENT. The information in the requirement usually specify the area, volume, and weight for each CARGO CATEGORY. The same MOVEMENT REQUIREMENT can have more than one CARGO CATEGORY but just one CARGO CLASS. than dry cargo.

SEALIFT RESOURCE can be classified in two broad categories. **COMMON USER SEALIFT ASSETS** and **NONCOMMON USER SEALIFT ASSETS.** COMMON USER or CONVENTIONAL RESOURCES are those militarily useful merchant ships available for joint support of all Service's MOVEMENT REQUIREMENTS. NONCOMMON USER RESOURCES are not generally available to transport joint MOVEMENT REQUIREMENTS [Joint-Pub-4.01.2, 1996].

COMMON USER RESOURCES can be divided into two categories:

1. **DRY CARGO** or **FREIGHTERS:** dry cargo ships are considered militarily useful if they can carry a minimum of 2,000 LONG TONS of cargo and the ability to carry unit equipment, ammunition, or sustaining supply. The types of DRY CARGO SHIPS are:

   (a) **BREAKBULK:** equipped with deck cranes.

   (b) **ROLL-ON/ROLL-OFF:** ship specifically designed to carry wheeled and tracked vehicles.

   (c) **CONTAINERSHIPS:** ship specifically designed to carry all of their cargo in standard ocean shipping **CONTAINERS**. CONTAINERSHIP capacity is usually expressed in **TWENTY-FOOT EQUIVALENT UNITS** which is defined as the number of 20'x 8' x 8'6" it can carry.

   (d) **BARGE :** ships designed to carry specially designed BARGES (LIGHTERS – 97'6" long, 35' wide, 16' 11" high) or a combination of LIGHTERS and CONTAINERS. Two types of BARGES are available:

      i. **LIGHTER ABOARD SHIP (LASH):** single decked vessel with large hatches, wing tank arrangements, and a clear access to the stern.

      ii. **SEABARGE (SEABEE):** three decks on which the cargo BARGES are stowed.

   (e) **DRY BULK CARRIERS:** carry grain or similar cargo in bulk.

2. **TANKERS:** a tanker is considered militarily useful if it can carry **PETROLEUM, OILS, and LUBRICANTS (POL),** and has a capacity in the range of 2,000 to 100,000 DWT (DEADWEIGHT measured in LONG TONS of 2,240 pounds). TANKERS are classified by size:

(a) **HANDY SIZE TANKERS:** carries from 48,000 to 280,000 BBLs or 6,000 to 35,000 DWT. Carries clean or refined products.

(b) **MEDIUM SIZE TANKERS:** carries from 280,000 to 800,000 BBLs or 35,000 to 100,000 DWT.

(c) **LARGE CRUDE CARRIERS:** dedicated to the transportation of crude oil can carry from 100,000 to 400,000 DWT.

NONCOMMON USER RESOURCE are:

1. **FAST SEALIFT SHIP (FSS):** former CONTAINERSHIPS purchased by the NAVY and transformed into RO / RO.

2. **AUXILIARY CRANE SHIP (ACS):** converted CONTAINERSHIPS on which heavy-lift cranes have been mounted. These ships can operate where port facilities are non-existent, inadequate, or damaged.

3. **HEAVY LIFT SHIPS** or **FLOAT-ON/FLOAT-OFF (FLO/FLO):** semi-submersible ships that provides the capability to load, transport, and offload outsized military cargo independent of port equipment traditionally used.

4. **AVIATION LOGISTICS SUPPORT SHIPS (T-AVB):** provide dedicated and rapid sealif to support Marine Corps aviation sustainment forces.

5. **HOSPITAL SHIPS (T-AH):** converted tankers with 12 operating rooms and 1,000 patient beds.

6. **LARGE MEDIUM SPEED ROLL-ON/ROLL-OF (LMSR):** faster and large RO / RO ship.

7. **AFLOAT PRE-POSITIONING FORCE (APF):** chartered commercial vessels or activated Ready Reserve Force vessels used to forward deploy equipment and supplies. The APF is composed of two types of ships:

   (a) **MARITIME PRE-POSITIONING SHIPS:** 13 specially constructed or modified RO / RO ships that are forward deployed in three self-contained squadrons.

   (b) **AFLOAT PRE-POSITIONS SHIPS:** government owned and commercially chartered ships on which pre-positioned military equipment, munitions, and supplies are store to meet rapid deployment requirements of various Services.

5.4.5 TRANSPORT TERMINALS

SEAPORTS and AIRPORTS are modeled as AGGREGATE RESOURCES that may or may not have associated SUB-RESOURCES. In general, an AIRPORT or SEAPORT contains a number of different sub-resources, each providing some type of AVAILABLE CAPACITY. However, depending of the level of modeling detail required, an AIRPORT or SEAPORT might alternatively be modeled strictly in terms of a single TERMINAL CAPACITY. In this case, the single estimate of AVAILABLE CAPACITY might reflect an aggregation of the AVAILABLE CAPACITY of several sub-resources, or it might reflect the fact that a single sub-resource provides the dominating capacity constraint.

Some examples of measurements for TERMINAL CAPACITY are:

1. **AIRPORT CAPACITY:**
   (a) **MAXIMUM ON GROUND:** maximum number of AIRCRAFT that can be simultaneously at the AIRPORT.
   (b) **NUMBER OF ON/OFFLOAD CREWS:** number of LIFTS that can be on-loaded or offloaded at the same time.
   (c) **PARKING SPACES:** number of LIFTS that can be at the TERMINAL.
   (d) **THROUGHPUT:** amount of cargo per unit of time that can flow through the AIRPORT.
2. **SEAPORT CAPACITY :**
   (a) **NUMBER OF BERTHS:** number of ships that can be at the SEAPORT.
   (b) **RECEPTION CAPACITY:** number of ships that can be berthed or anchored in a harbor or at a SEAPORT.
   (c) **DISCHARGE CAPACITY:** cumulative amount of cargo that can be discharged from each of the berths and anchorages.
   (d) **TRANSFER CAPACITY:** total capability to transfer cargo from ship side to storage, measured in cargo units per unit of time.
   (e) **STORAGE CAPACITY:** amount of cargo that can be stored at any one time.
   (f) **TERMINAL CLEARANCE CAPACITY:** ability of moving cargo away from the terminal, measured in tonnage per units of time.
   (g) **THROUGHPUT** the minimum of RECEPTION, DISCHARGE, or CLEARANCE capacity.

5.5 ACTIVITIES

5.5.1 Concept Definition.

An **ACTIVITY** represents a process that can be executed over a certain time interval. An ACTIVITY requires RESOURCES to execute and its execution both depends on and affects the current state of these RESOURCES. An ACTIVITY can also have other EFFECTS (e.g., PRODUCTS are produced, other enabling RESOURCE states are established), and it is these EFFECTS that lead ultimately to satisfied DEMANDS. An ACTIVITY may be decomposable into a set of more-detailed SUB-ACTIVITIES, enabling processes to be described at multiple levels of abstraction. Figure 5.10 summarizes the activity representation.

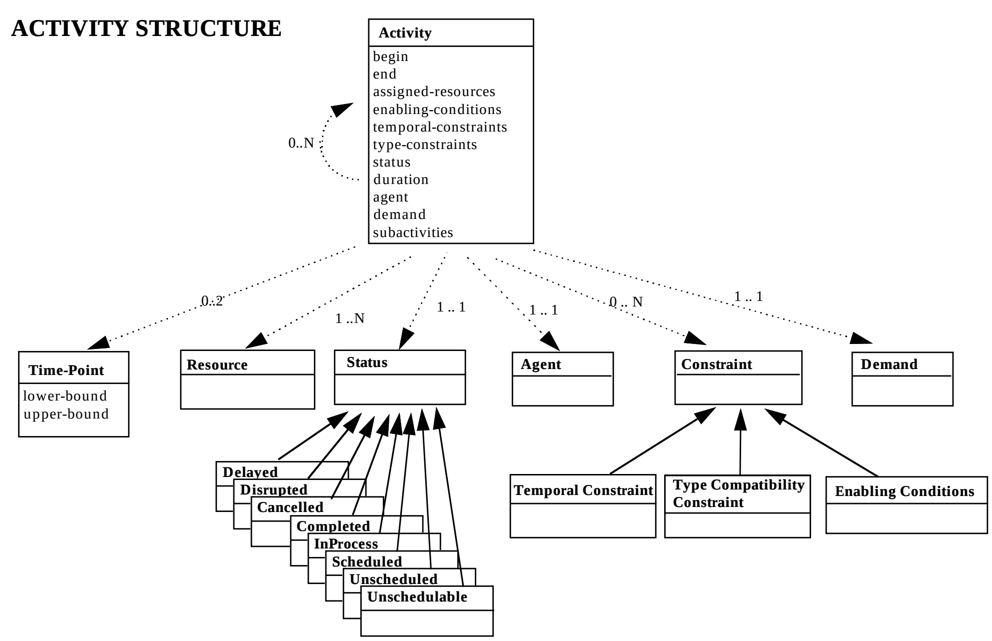

Figure 5.10: ACTIVITY Structure

The OZONE ontology and associated problem solving capabilities center around the ACTIVITY entity. PRODUCTS, DEMANDS, and RESOURCES define the set of ACTIVITIES to be scheduled and executed. All the requirements specified in the DEMAND, the special conditions established by the PRODUCT, and the physical and technological aspects of RESOURCE usage are translated into a set CONSTRAINTS that directly affect the ACTIVITIES. [Gruninger & Fox, 1994] defines ACTIVITY as *the basic transformational action primitive with which processes and operations can be represented; it specifies how the world is changed.* The conditions that should hold in order for the ACTIVITY be executed are called **ENABLING STATE,** and the conditions that hold after the ACTIVITY has been executed are called **CAUSED STATE.**

A similar definition of ACTIVITY is provided by [Uschold *et al.*, 1996]: an ACTIVITY *is something done over a particular time interval.* An ACTIVITY has **PRE-CONDITIONS**, **EFFECTS,** is performed by one or more **DOERS,** can be decomposed into **SUB-ACTIVITIES,** use or consumes RESOURCES, has **AUTHORITY** requirements, and has an associated **OWNER.** The state of the world in the enterprise ontology is designated by **STATE of AFFAIRS.** An important concept associated to this definition of ACTIVITY is the concept of **DOER, ACTOR** or **AGENT,** the entity that performs the ACTIVITY. Considering the ACTOR entity, [Tate, 1996] makes a distinction between **ACTION** and **EVENT:** An ACTION is an ACTIVITY done, performed, or executed by a known AGENT; while an EVENT is an ACTIVITY done by an unknown AGENT. An EVENT is an ACTIVITY outside the scope of the model and only its EFFECTS are relevant.

We want to be more precise about the concept of agency. In the OZONE ontology, an AGENT associated to an ACTIVITY is an entity, e.g. person, a group of people, a human organization, or computer system, that plans, establishes, authorizes, owns, schedules, or executes the ACTIVITY. In this sense, an AGENT **uses** a RESOURCE to process an ACTIVITY. In some cases, (e.g., the crew of an aircraft) a RESOURCE may simultaneously assume the role of the AGENT.

For administrative purposes, three types of AGENTS can be identified:

- **ACTOR:** the motive force behind the ACTIVITY [Tate, 1997]. The ACTOR is the agent that create the conditions necessary for the execution of the ACTIVITY.
- **RESPONSIBLE AGENT** or **OWNER:** the AGENT responsible for the execution of the ACTIVITY[Uschold *et al.*, 1996]. Being responsible means having the capability of performing the ACTIVITY but does not mean actually executing the ACTIVITY. For example, USTRANSCOM would be the RESPONSIBLE AGENT or OWNER of activities established by fulfill peacetime AIRLIFT MOVEMENT REQUIREMENTS but the ACTOR would be the AIR MOBILITY COMMAND.
- **AUTHORIZING AGENT:** the AGENT that has the right to establish, cancel, schedule, or allow the execution of the ACTIVITY. AUTHORITY does not imply *capability.* For example, the Joint Chiefs of Staff has the ability

of planning and scheduling ACTIVITIES to satisfy PEACETIME MOVEMENT REQUIREMENTS but USTRANSCOM is the agent that has the ownership of these ACITIVITES. The AUTHORITY also implies the right to change ownership.

5.5.2 Properties

From the standpoint of the problem solver, an ACTIVITY designates a set of decision variables. The action of *scheduling* an ACTIVITY involves determining values for these variables. The basic decision variables associated with an ACTIVITY are:

- **START-TIME, END-TIME**, TIME POINTS which delineate the interval during which the ACTIVITY will occur. START-TIME and END-TIME are established based on the DATES specified in the DEMAND and RESOURCE availability. The ACTIVITY starts being processed exactly at the START-TIME and ends being processed immediately before its END-TIME.
- **ASSIGNED-RESOURCES**, which indicates the set of RESOURCES allocated to the ACTIVITY. The RESOURCES in this set are capable of processing the ACTIVITY without violating any hard or non-relaxable CONSTRAINTS.

An ACTIVITY has a number of properties that constrain the values that can be assigned to these decision variables:

- **DURATION:** the time required for the ACTIVITY to execute. The DURATION is usually a joint property of ACTIVITY and RESOURCES. For example, the DURATION of a TRANSPORT ACTIVITY depends on the velocity of the RESOURCE used.
- **ENABLING-CONDITIONS:** the STATE OF AFFAIRS that should hold for the ACTIVITY to start executing. This correspond to a set of constraints, represented as logical predicates, that must be satisfied for the ACTIVITY to execute. A constraint being satisfied is modeled as a predicate or logical *well-formed* expression evaluating to its true value.

  Certain conditions are inherent to the ACTIVITY itself and others are created as a result of the decision being made. Figure 5.11 shows an example of such conditions. In the transportation domain, the condition for executing any TRANSPORT ACTIVITIES is that the lifter or transportation resource be in the same location as the cargo to be moved and that there

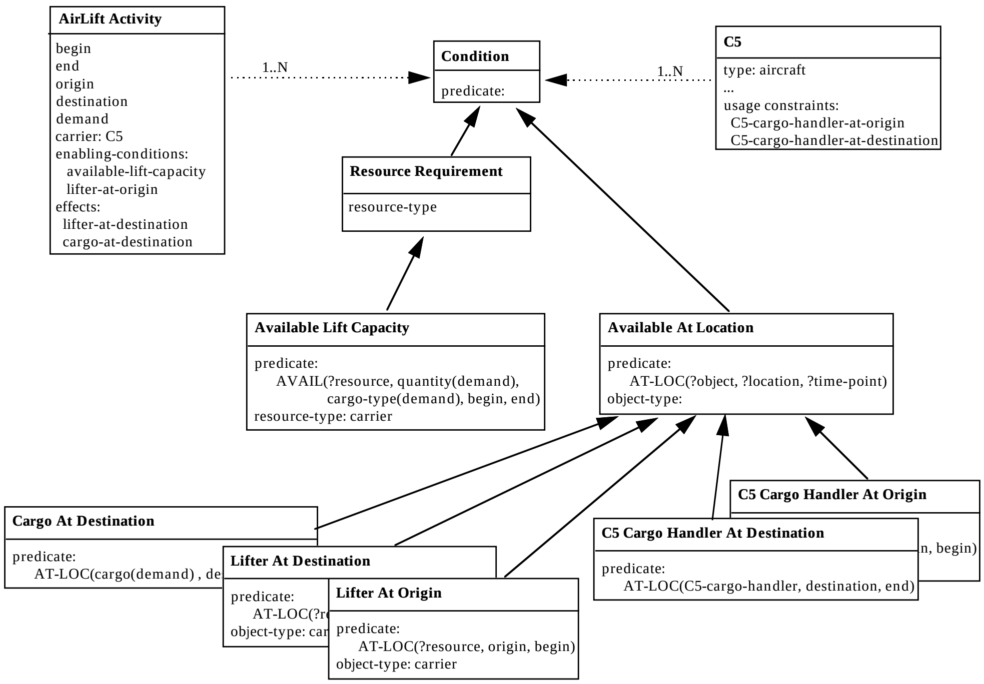

Figure 5.11: ACTIVITY Enabling Conditions

be available capacity on the lifter. These conditions are the same for all TRANSPORT ACTIVITIES. However, the use of a C5 as the lifter, requires additional elements to be added to the set of conditions that should hold for the ACTIVITY to be executed. The use of a C5 as the lifter requires, for example, that special cargo handling equipment be available during both ON-LOAD and OFFLOAD.

- **EFFECTS:** similar to the ENABLING CONDITIONS, the EFFECTS are the set of conditions that will hold by the time the ACTIVITY finishes execution. These conditions are also modeled as a set of predicates or *well-formed* logical expressions that evaluate to true when the ACTIVITY finishes execution. As ACTIVITIES finish just before their END-TIMES, we can say that the conditions described in the EFFECTS are true exactly at and after the ACTIVITY's END-TIME. Using the example of figure 5.11, after the AIRLIFT ACTIVITY arrives at its DESTINATION, the conditions *AT(cargo, destination, end-time)*, *AT(C5, destination, end-time)*, and *AT (c5-cargo-handler, destination, end-time)* all evaluate to true. If the state resulting from the execution of ACTIVITIES satisfy the conditions established by the PRODUCT specified in the DEMAND, then we say that the DE-

MAND has been satisfied.

- **RELATIONS:** the set of explicitly represented CONSTRAINTS between this ACTIVITY and others. RELATIONS establish restrictions on the set of possible values for certain properties or attributes. Examples of RELATIONS between activities are:

  – **SAME VALUE:** this relation requires certain attributes of two differents ACTIVITIES to have the same value. For example, in a AIRLIFT MISSION with two legs, the ORIGIN of the second leg and the DESTINATION of the first should have the same value.

  – **DIFFERENT VALUE:** this relation requires certain attributes of two different ACTIVITIES to have different values. For example, TRANSPORT ACTIVITIES carrying ammunition could not use the same port as TRANSPORT ACTIVITIES carrying passengers.

  An important type of RELATION between ACTIVITIES is the class of **TEMPORAL RELATIONS** that restricts the set of valid time intervals in which an ACTIVITY can be processed. TEMPORAL RELATIONS can be reduced to the general case of simple relation between attributes. However, given their importance to the scheduling process, we prefer to treat them as a special and separated class of constraints. See section 5.14 for more details about RELATIONS.

- **DEMAND:** the DEMAND that the ACTIVITY was instantiated to satisfy. The DEMAND is the mechanism used to impose user specified constraints on the ACTIVITY. The DEMAND RELEASE DATE imposes a lower bound on the START TIME of the ACTIVITY, this lower bound is the **EARLIEST-START-TIME.** The DEMAND DUE DATE imposes an upper bound on the END-TIME of the ACTIVITY; this upper bound is the **LATEST-FINISH-TIME.** Relative priorities between DEMANDS is transferred to their respective ACTIVITIES. The higher the DEMAND LEVEL OF SPECIFICATION, the more constrained the ACTIVITY. For example, the specification of the PORT-OF-EMBARKATION and PORT-OF-DEBARKATION restricts the set of TRANSPORTATION RESOURCE that can be used to process the ACTIVITY.

- **PARAMETERS:** depending on the type of ACTIVITY, there may be one or more PARAMETERS relating to the ACTIVITY's associated DEMAND. For example, if the associated DEMAND is for a QUANTITY of some PRODUCT, then the ACTIVITY might also have a QUANTITY, in this case indicating the portion of the total QUANTITY that it produces.

- **DERIVATIVE DEMANDS:** Internally generated DEMANDS is also a property of the ACTIVITY responsible for their creation. This is required because if the ACTIVITY gets unscheduled or canceled, the dependent

DERIVATIVE DEMANDS also need to be unscheduled or removed from the system. Figure 5.12 shows an example of how DERIVATIVE DEMANDS are created. The ENABLING CONDITIONS of the ACTIVITY requires a state that cannot be satisfied given the current STATE OF AFFAIRS. The unsatisfiable condition, however, matches the ACHIEVEMENT CONDITION of one of the known PRODUCTS or DEMAND OBJECTIVES available. The system then, knowing that such a condition can be satisfied, generates an internal request for this objective or PRODUCT. The relationship between this new DEMAND and the ACTIVITY that originated it is maintained by adding the DEMAND to the list of DERIVATIVE DEMANDS of the ACTIVITY. By scheduling and processing the ACTIVITIES generated by the DERIVED DEMAND, would cause the ENABLING CONDITIONS of the original ACTIVITY to be satisfied. Consequently, the previously UNCHEDULABLE ACTIVITY can now be scheduled and processed.

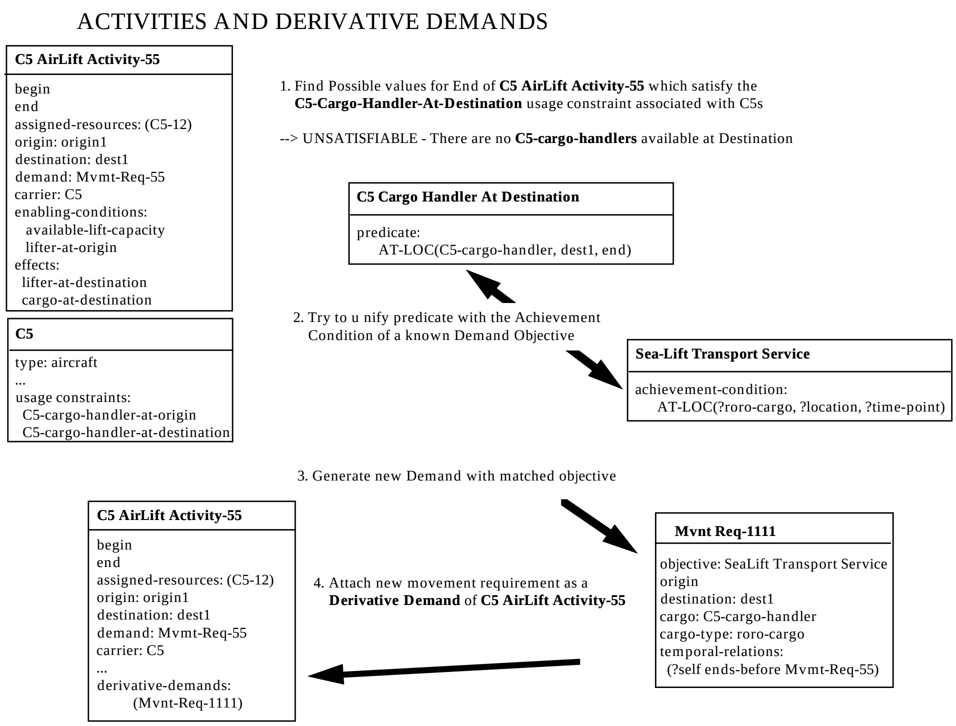

Figure 5.12: Derivative Demands

- **AGENT** or **ACTOR:** the entity responsible for or the entity that actually process the ACTIVITY. If required, additional properties can be defined to identify ACTOR, RESPONSIBLE AGENT, and AUTHORIZING AGENT.

For a general ACTIVITY, only the ACTOR or AGENT property is usually sufficient.

- **STATUS:** depending on the value assigned to its decision variables, the current value of time, and the previous state, an ACTIVITY may be in one of several states:

  1. **UNSCHEDULED:** no RESOURCE has yet been assigned to process the ACTIVITY.
  2. **UNSCHEDULABLE:** there is no set of RESOURCES in the set of available resources that satisfies all the ENABLING-CONDITIONS of the ACTIVITY.
  3. **SCHEDULED:** a set of RESOURCES has been assigned to the ACTIVITY and the assigned START-TIME is later the CURRENT-TIME.
  4. **CANCELLED:** the ACTIVITY has been scheduled but at a time point before its assigned START-TIME, its execution has not been authorized to start. A CANCELLED ACTIVITY is not supposed to be processed.
  5. **DELAYED:** the ACTIVITY has been scheduled, its assigned START-TIME is before the CURRENT-TIME and the processing of the ACTIVITY has not been started. DELAYED ACTIVITIES are supposed to be processed by the same set of RESOURCES at a later time.
  6. **IN-PROCESS:** a set of RESOURCES has been assigned to the ACTIVITY, the assigned START-TIME is earlier than CURRENT-TIME, the assigned END-TIME is later than the CURRENT-TIME, and the ACTIVITY has not been INTERRUPTED or TERMINATED.
  7. **COMPLETED:** a set of RESOURCES has been assigned to the ACTIVITY, the assigned END-TIME is earlier than CURRENT-TIME, the processing of the ACTIVITY has been started, and the ACTIVITY has not been INTERRUPTED or TERMINATED. This means that the ACTIVITY completed successfully.
  8. **INTERRUPTED** or **DISRUPTED :** a set of RESOURCES has been assigned to the ACTIVITY, the assigned START-TIME is earlier than the CURRENT-TIME, the assigned END-TIME is later than the CURRENT-TIME, the processing of the ACTIVITY has been started suspended at a time point before its assigned END TIME. An INTERRUPTED activity is supposed to be completed at a later time.
  9. **TERMINATED:** a set of RESOURCES has been assigned to the ACTIVITY, the assigned END-TIME is earlier than CURRENT-TIME, the processing of the ACTIVITY has been started and has been suspended before its assigned END TIME. A TERMINATED ACTIVITY is not supposed to be completed.

- **CHILDREN, PARENTS:** ACTIVITIES are aggregate entities. SUB-ACTIVITIES provides a higher LEVEL OF DETAIL or a higher LEVEL OF ABSTRACTION. Changes in the STATUS of children are reflected in the STATUS of the ACTIVITY. For example, an aggregate ACTIVITY is only considered SCHEDULED when all its CHILDREN has been scheduled. The same for COMPLETED. An ACTIVITY will be considered UNSCHEDULED, UNSCHEDULABLE, CANCELLED, DELAYED, IN-PROCESS, INTERRUPTED, or TERMINATED if at least one of its CHILDREN has STATUS UNSCHEDULED, UNSCHEDULABLE, CANCELLED, DELAYED, IN-PROCESS, INTERRUPTED, or TERMINATED respectively.

Following a constraint-based problem solving orientation, an ACTIVITY provides capabilities for incrementally allocating resources and making variable assignments (*Reserve-Resources*), for retracting previous assignments (*Free-Resources*), and for propagating the consequences of these decisions to related ACTIVITIES (*Propagate-Constraints*). An ACTIVITY thus maintains EARLIEST and LATEST bounds on its START-TIME and END-TIME, as well as a set of currently feasible RESOURCE-ALTERNATIVES. An ACTIVITY also defines primitives for exploring alternative sets of resource assignments (*Find-Alternative-Resources*) and alternative intervals where resources are simultaneously available (*Find-Schedulable-Time*).

5.5.3 TRANSPORT ACTIVITIES

To satisfy transportation MOVEMENT REQUIREMENTS, two basic types of ACTIVITIES are used. One type corresponds to the ACTIVITY that uses the TRANSPORTATION RESOURCE to move the required cargo between geographic LOCATIONS. This type of ACTIVITY is called, as expected, **TRANSPORT ACTIVITY.** The other type corresponds to the set ACTIVITIES required to prepare the cargo and the TRANSPORTATION RESOURCES to perform the movement specified in the requirement. These class of ACTIVITIES is generically designated as **LOAD OPERATIONS.**

A TRANSPORT ACTIVITY has three additional properties:

- **ORIGIN:** the initial geographic LOCATION from where the cargo is to be moved by this ACTIVITY. The ORIGIN of the TRANSPORT ACTIVITY does not need to be the ORIGIN specified in the MOVEMENT REQUIREMENT. The ORIGIN of the TRANSPORT ACTIVITY is only one of the PORT-OF-EMBARKATIONS specified in the ITINERARY that has been specified in the requirement or selected by the scheduler.

- **DESTINATION:** the final geographic LOCATION to where the cargo is to be moved by this ACTIVITY. The DESTINATION of the TRANSPORT ACTIVITY does not need to be the DESTINATION specified in the MOVEMENT REQUIREMENT. The DESTINATION of the TRANSPORT ACTIVITY is only one of the PORT-OF-DEBARKATIONS specified in the ITINERARY that has been specified in the requirement or selected by the scheduler.

- **AUXILIARY ACTIVITIES:** The set of all the ground ACTIVITIES required to prepare the cargo to be moved, load it into the lifter, and deliver it to its final destination. Although AUXILIARY ACTIVITIES also require the allocation of RESOURCES, they have a secondary importance for the scheduler. No additional reasoning besides verifying RESOURCE availability is required.

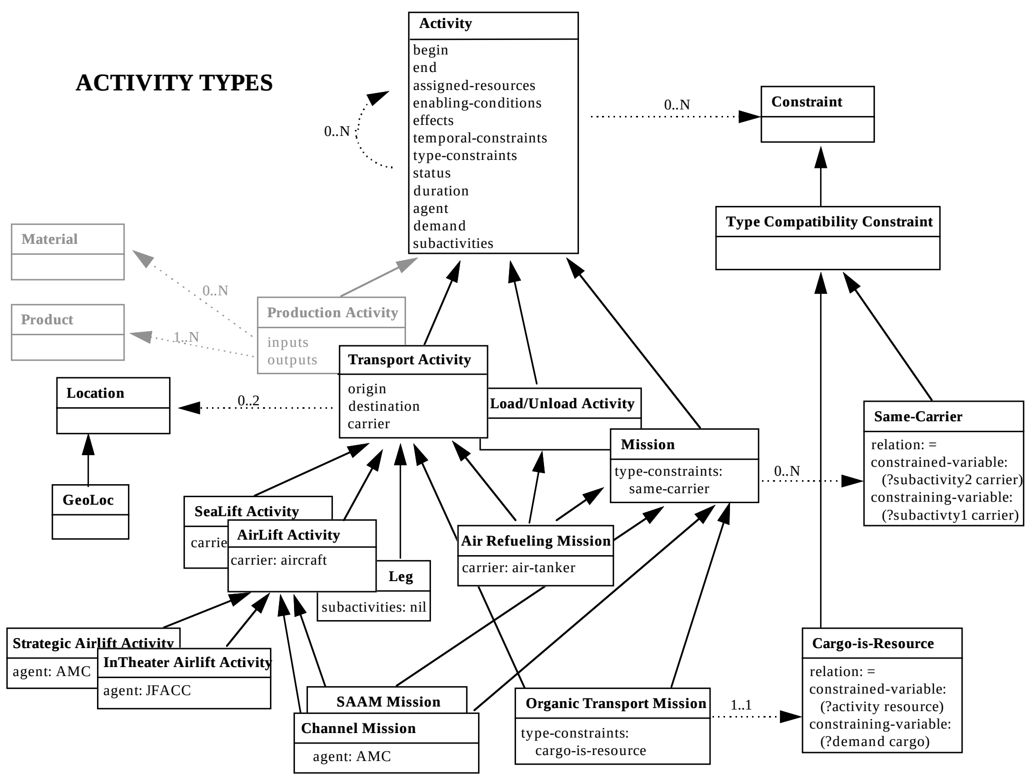

Figure 5.13: ACTIVITY Types

LOAD-OPERATIONS are not modeled to a very high level of detail. We recognize that port operation is an important part of the overall transportation process but defining a more detailed model would only create an extra burden to the scheduling engine and it is not clear the benefits of having a more detailed port representation.

TRANSPORT ACTIVITIES, if required, can be further specialized according to the transportation mode or to the type of service being provided. In figure 5.13 we show examples of such specialization. A **SEALIFT ACTIVITY** is an ACTIVITY that can only use a SEALIFT RESOURCES and whose ORIGIN and DESTINATION can only be SEAPORTS. An **AIRLIFT ACTIVITY** is an ACTIVITY that can only use AIRLIFT RESOURCES and whose ORIGIN and DESTINATION can only be AIRPORTS. A **TRANSPORT MISSION** is an aggregate TRANSPORT ACTIVITY that requires all its CHILDREN or SUB-ACTIVITIES to use the same lift, and imposes temporal and spatial synchronization on the execution of these SUB-ACTIVITIES. The ITINERARY and/or ROUTE of a MISSION is specified in its MOVEMENT REQUIREMENT. We refer to the SUB-ACTIVITIES of a MISSION as a a **MISSION LEG.** A MISSION LEG is a TRANSPORTATION ACTIVITY that has no children; it is the single direct movement between two consecutives locations specified in the ITINERARY of the MISSION.

1. **AIRLIFT ACTIVITY,** according to the type of TRANSPORT SERVICE provided (see section 5.3.3) can be further divided, for example, into:
   (a) **STRATEGIC AIRLIFT**
      i. **STRATEGIC DEPLOYMENT ACTIVITY**
      ii. **STRATEGIC RE-DEPLOYMENT ACTIVITY**
      iii. **SUSTAINMENT AIRLIFT ACTIVITY**
         A. **CHANNEL MISSION**
         B. **AIR MOBILITY EXPRESS MISSION**
         C. **SPECIAL ASSIGNMENT AIRLIFT MISSION**
   (b) **TEATHER AIRLIFT**
      i. **CHANNEL MISSION**
      ii. **SPECIAL ASSIGNMENT AIRLIFT MISSION**
   (c) **ORGANIC AIRLIFT**
2. **SEALIFT ACTIVITIES** can be divided according to the phase of DEPLOYMENT. This division correspond to the different types of services provided. A generic classification of SEALIFT ACTIVITIES would be:
   (a) **PRE-POSITIONING ACTIVITY**
   (b) **SURGE PHASE ACTIVITY**
   (c) **TACTICAL RESUPPLY ACTIVITY**
   (d) **SUSTAINED RESUPPLY ACTIVITIES**
   (e) **RE-DEPLOYMENT ACTIVITIES**

3. **LOAD-ACTIVITY** is the class of the AUXILIARY ACTIVITIES. The only additional property of a LOAD-OPERATION is the **LOAD-OWNER.** The value of the LOAD-OWNER property is the main TRANSPORT ACTIVITY that has this LOAD-OPERATION as an auxiliary ACTIVITY. We identify two basic types of LOAD-OPERATIONS:

   (a) **ON-LOAD:** The ACTIVITY of preparing the cargo and loading it into the lifter. The ON-LOAD ACTIVITY requires port available capacity and requires the lift to be at the port during its entire duration. Port capacity can be represented as maximum number of lifters that can be at the port at the same time, maximum number of lifters being serviced at the same time, maximum throughput, etc.

   (b) **OFFLOAD** Similarly to the ON-LOAD, the OFFLOAD is the ACTIVITY of removing the cargo from the lifter and preparing it to be moved to some other location in the same port.

   The **ON-LOAD** for **AIRLIFT ACTIVITIES** can be divided into:

   (a) **MARSHALLING ACTIVITY:** preparation of the cargo to be loaded into the aircraft or to be moved after offload. These ACTIVITIES do not require the lift to be at the port but requires additional RESOURCES like a MARSHALLING yard and RESOURCES capable of moving the cargo.

   (b) **ON-LOADING ACTIVITY:** the actual loading of the cargo inside the aircraft.

   The **OFFLOAD** for **AIRLIFT ACTIVITIES**, depending on the method of delivery, can be specialized into:

   (a) **AIR-LAND ACTIVITY:** airlifted personnel and material are disembarked, unloaded, or unslung from an aircraft after it has landed[Joint-Pub-3-17, 1995]. AIRLAND ACTIVITIES may also involve **OFFLOADING** the plane and **MARSHALLING** the cargo.

   (b) **AERIAL DELIVERY:** airlifted personnel and material are disembarked or unloaded from the aircraft still in flight. Types of AERIAL DELIVERY of AIRDROP are:

      i. **FREE DROP:** no parachute used.
      ii. **HIGH VELOCITY DROP:** pilot parachutes used.
      iii. **LOW VELOCITY DROP:** cargo parachutes used.
      iv. **LOW-ALTITUDE PARACHUTE EXTRACTION SYSTEM (LAPES):** extraction of the cargo from the aircraft flying at a low altitude of only 5 to 10 feet above ground using special parachutes

The operations of water terminals is particularly critical given the amount and size of cargo to be loaded to and unloaded from sealifts. We can divide the water terminal ACTIVITIES into:

(a) **RECEPTION ACTIVITY:** ACTIVITY required to position the ship in a place where it can be loaded or unloaded.
(b) **LOAD ACTIVITY:** Transfer of the cargo from the shipside to the interior of the ship.
(c) **DISCHARGE ACTIVITY:** Removal of the cargo from inside the ship to the ship side.
(d) **TRANSFER ACTIVITY :** Transfer of the cargo from shipside to storage area or from storage or marshalling area to ship side.
(e) **CLEARANCE ACTIVITY:** movement of cargo away from terminal.
(f) **MARSHALLING ACTIVITY:** preparation of the cargo to be loaded into the ship or to be moved after DISCHARGE and TRANSFER.

An interesting aspect of the EFFECTS of a TRANSPORTATION ACTIVITY is the possible increase in the number of available RESOURCES as pieces of cargo suddenly become RESOURCES when delivered at the DESTINATION. For example, a truck moved in a ship, can be used to move the remaining cargo from the terminal to the AREA OF OPERATIONS. By the END-TIME of the TRANSPORT ACTIVITY that brought the truck, the amount of cargo to be moved decreases and the available RESOURCE CAPACITY increases. This would cause a situation similar to the example presented in figure 5.11. The use of this truck is conditioned on the execution of the TRANSPORT ACTIVITY. For any other ACTIVITY requiring to use this truck, an additional ENABLING CONDITION requiring the previously scheduled TRANSPORT ACTIVITY that brings the truck to finish before the start of the current ACTIVITY.

Another related aspect is the fact that some cargo is capable of moving itself. Using the example of the truck again, a requirement for a certain unit containing trucks as it cargo, would move itself from the ORIGIN to the PORT-OF-EMBARKATION, would be loaded into the lift, moved to the PORT-OF-DEBARKATION, and would again move itself to the final DESTINATION. This duality resource-cargo creates a problem for tracking cargo. In the current representation, each TRANSPORT ACTIVITY accounts its own cargo and the assigned RESOURCES are supposed to have at least enough capacity for the cargo specified in the ACTIVITY. The available capacity of a RESOURCE usually does not include its own dimensions. If the cargo becomes a RESOURCE, we would need or to reduce the QUANTITY of cargo specified in the DEMAND or modify the RESOURCE available capacity to consider its own dimensions. However, if we modify the RESOURCE capacity, this increased capacity is only valid for this particular request. If any other requirement want to use this RESOURCE, the available capacity would be the cargo carrying capacity available.

5.6 CONSTRAINTS

5.6.1 Concept Definition.

Generally speaking, a **CONSTRAINT** restricts the set of values that can be assigned to a variable. In basic scheduling models, CONSTRAINTS restrict the assignment of START and END-TIMES and the allocation of RESOURCES to ACTIVITIES. In richer domains like transportation planning and scheduling there are generally additional decision variables (e.g., origins, destinations) and associated constraints to take into account. Also, there are other dynamic aspects of the world in addition to resource availability that affect the execution of activities.

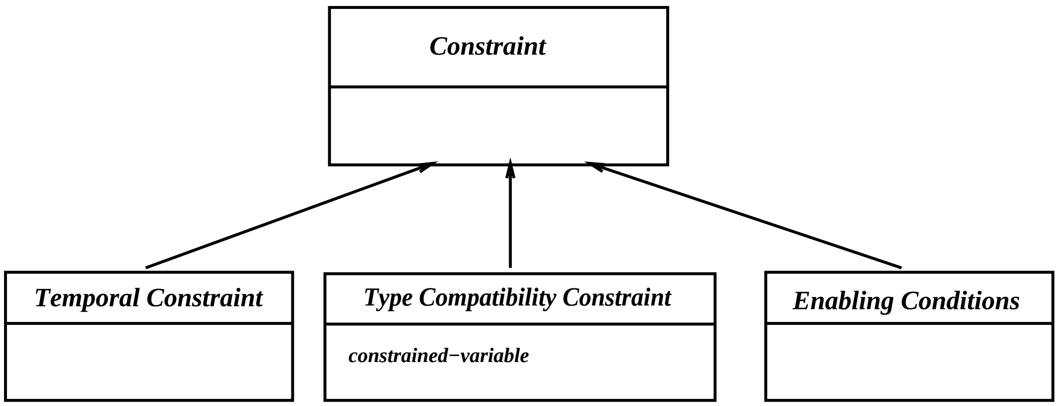

Figure 5.14: Basic CONSTRAINTS Types

Given this perspective, we can identify three basic types of constraint (see Figure 5.14):

- **TYPE CONSTRAINTS** restrict the values of non-temporal decision variables, and specify conditions under which a value assignment to a given variable is compatible with those of other variables or properties in the model.
- **TEMPORAL-CONSTRAINTS** restrict the values of temporal decision variables, i.e., ACTIVITY START-TIMES and END-TIMES.
- **WORLD-CONDITIONS** specify conditions that must hold in the current WORLD-STATE for an ACTIVITY to feasibly execute.

These types of constraints are discussed individually in the subsections below.

TYPE CONSTRAINTS

A **TYPE CONSTRAINT** (Figure 5.15) restricts the value (or type) of a designated CONSTRAINED-VARIABLE, which can be any non-temporal decision variable. There are two basic forms:

1. **VALUE RELATION** - A VALUE RELATION specifies a binary constraint between the CONSTRAINED VARIABLE and a second CONSTRAINING VARIABLE. It defines a relative restriction on the possible values that can be taken on by both variables. Two common RELATIONS, $=$ and $\neq$, give rise to the following VALUE RELATION constraints:

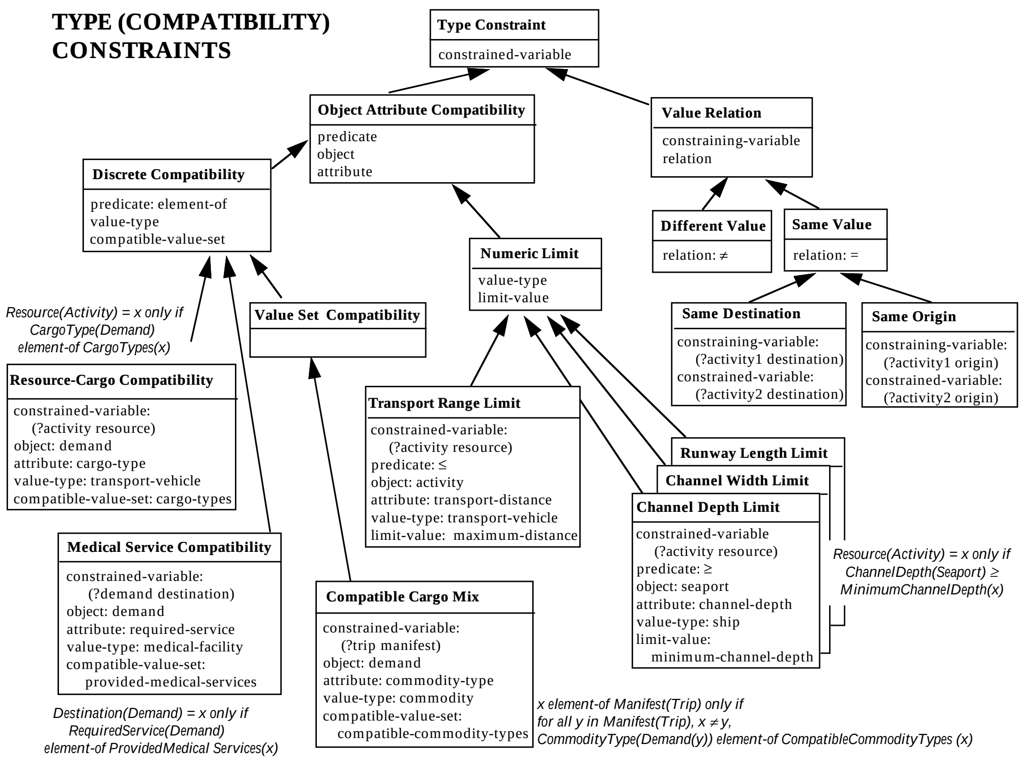

Figure 5.15: Type (Compatibility) Constraints

(a) **SAME VALUE** - For 2 variables A and B, A SAME-VALUE B implies that value(A) = value(B). Two specializations of SAME-VALUE important for transportation planning are:

- **SAME-ORIGIN** and **SAME-DESTINATION** constraints restrict the ORIGINS (resp. DESTINATIONS) of two ACTIVITIES to have the same value. Such relations are needed, for example, to enforce UNIT-INTEGRITY (see below).
- **SAME-CARRIER** - This constraint asserts that the CARRIER resource assigned to two given TRANSPORT ACTIVITIES must be the same. This relation is used to define the concept of a MISSION.
- **CARGO-IS-RESOURCE** - This relation constrains the CARRIER resource that is assigned to a given ACTIVITY a to be the same as the value (entity) designated as the CARGO in a's associated MOVEMENT REQUIREMENT. This constraint is a defining aspect of an ORGANIC TRANSPORT MISSION.

(b) **DIFFERENT-VALUE** - For 2 variables A and B, A DIFFERENT-VALUE B implies that value(A) $\neq$ value(B).

2. **VALUE COMPATIBILITY** - A VALUE COMPATIBILITY specifies a necessary condition (or filter) on the possible values that a given CONSTRAINED-VARIABLE can assume, based on the compatibility of a candidate value with the value of some other variable (or ¡object attribute¿ pair) in the model. In the case of basic scheduling models, these CONSTRAINTS relate specifically to RESOURCE assignment decisions and are referred to as **RESOURCE-COMPATIBILITY CONSTRAINTS**. They designate the conditions under which a given RESOURCE (or type of RESOURCE) can be feasibly used to perform a given ACTIVITY. They may represent physical capabilities and limitations of RESOURCES, or external (e.g., user-imposed) restrictions.

   More precisely, A VALUE COMPATIBILITY specifies an <*OBJECT ATTRIBUTE*> pair, indicating the specific value that the CONSTRAINED VARIABLE must be compatible with, a VALUE-TYPE, which specifies the type of the CONSTRAINED-VARIABLE, and a PREDICATE, which specifies the compatibility condition that must be satisfied. Dependent on the specific form of VALUE COMPATIBILITY defined (see below), a particular COMPATIBILITY-ATTRIBUTE of VALUE-TYPE is also specified to provide the second argument to PREDICATE. Generally speaking, a compatibility states that *x = value (CONSTRAINED-VARIABLE) only if value (ATTRIBUTE (OBJECT)) PREDICATE value (COMPATIBILITY-ATTRIBUTE (x))*.

   Two basic subtypes of VALUE COMPATIBILITY are:

   (a) **DISCRETE COMPATIBILITY** - A DISCRETE-COMPATIBILITY specifies that the value of <*OBJECT ATTRIBUTE*> must be an *element of* a designated COMPATIBLE-VALUE-SET of the VALUE-TYPE in order for a value x of type VALUE-TYPE to be a feasible assignment to CONSTRAINED-VARIABLE. Some examples of DISCRETE-COMPATIBILITY constraints from the transportation planning and scheduling domain include:

      - **RESOURCE-CARGO COMPATIBILITY** - A RESOURCE of type R can be assigned as the CARRIER of a TRANSPORT-ACTIVITY A only if the CARGO-TYPE specified in A's associated MOVEMENT REQUIREMENT is an element of the set of CARGO TYPES transportable by resources of type R.
      - **MEDICAL SERVICE COMPATIBILITY** - A FACILITY of type R can be assigned as the DESTINATION of a PATIENT-EVACUATION-REQUEST only if the REQUIRED-MEDICAL-SERVICE specified in the PATIENT-EVACUATION-REQUEST is one of the PROVIDED-MEDICAL-SERVICES of R.

   In the case of multi-valued variables, a DISCRETE COMPATIBILITY constraint can be defined simultaneously for all current values. This subtype of DISCRETE COMPATIBILITY is a called a **VALUE SET COMPATIBILITY**. An example from the the transportation planning and scheduling domain is:

- **COMPATIBLE CARGO MIX** - A COMMODITY x can be included in the MANIFEST of a given TRIP only if, for all COMMODITIES $y \neq x$ that are currently in the MANIFEST, the COMMODITY-TYPE of y is an element of the set of COMPATIBLE-COMMODITY-TYPES of x.

(b) **NUMERIC LIMIT** - A NUMERIC LIMIT specifies a quantitative relationship that must hold between the value of $<$*OBJECT ATTRIBUTE*$>$ and a designated LIMIT-VALUE attribute of the VALUE-TYPE in order for a value x of type VALUE-TYPE to be a feasible assignment to CONSTRAINED-VARIABLE. Many types of restrictions on resource usage are expressible as NUMERIC LIMIT constraints. For example,

- **TRANSPORT RANGE LIMIT:** A TRANSPORT VEHICLE R can be assigned to a TRANSPORT ACTIVITY only if the transport distance to be covered is $\leq$ the MAXIMUM TRANSPORT DISTANCE of R.
- **CHANNEL DEPTH LIMIT:** A SHIP R can be assigned to a SEALIFT ACTIVITY only if the CHANNEL DEPTH of the ORIGIN (DESTINATION) ports $\geq$ R's MINIMUM CHANNEL DEPTH.
- **CHANNEL WIDTH LIMIT:** A SHIP R can be assigned to a SEALIFT ACTIVITY only if the CHANNEL WIDTH of the ORIGIN (DESTINATION) ports $\geq$ R's MINIMUM CHANNEL WIDTH.
- **RUNWAY LENGTH LIMIT:** An AIRCRAFT R can be assigned to a AIRLIFT ACTIVITY only if the RUNWAY LENGTH of the ORIGIN (DESTINATION) ports $\geq$ R's MINIMUM RUNWAY LENGTH.

TEMPORAL CONSTRAINTS

TEMPORAL-CONSTRAINTS restrict the values of temporal decision variables, i.e., ACTIVITY START-TIMES and END-TIMES. There are two basic types:

1. An **ABSOLUTE-TIME-CONSTRAINT** places an absolute lower or upper bound on the value of a TIME-POINT. Some generic examples of ABSOLUTE-TIME-CONSTRAINTS previously mentioned include the RELEASE-DATE CONSTRAINT and the DUE-DATE CONSTRAINT (imposed by a DEMAND). More specifically in the transportation planning and scheduling domain, some examples of absolute time constraints include:

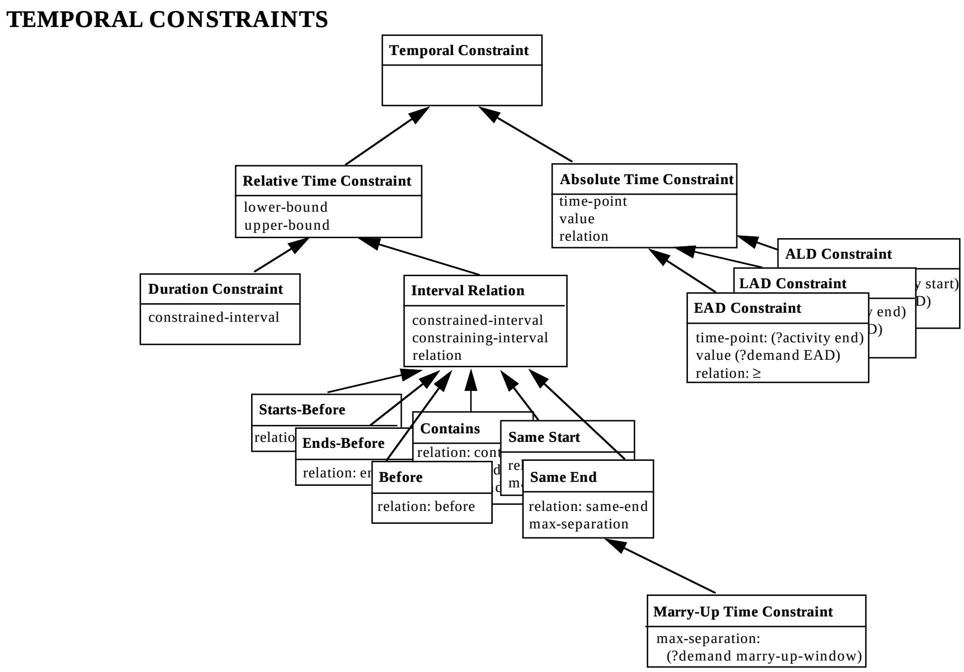

Figure 5.16: Temporal Constraints

- **EAD CONSTRAINT** - For a given ACTIVITY *a*, *End_Time(a)* $\geq$ *EARLIEST-ARRIVAL-DATE (MOVEMENT-REQUIRMENT(a))*
- **LAD CONSTRAINT** - For a given ACTIVITY *a*, *End_Time(a)* $\leq$ *LATEST-ARRIVAL-DATE (MOVEMENT-REQUIRMENT(a))*
- **ALD CONSTRAINT** - For a given ACTIVITY *a*, *Start_Time(a)* $\geq$ *AVAILABLE-TO-LOAD-DATE (MOVEMENT-REQUIREMENT(a))*

2. A **RELATIVE-TIME-CONSTRAINT**, alternatively, restricts the separation between two TIME-POINTS. According to whether or not the constrained TIME-POINTS belong to the same interval or not, we define two subtypes:

   (a) **INTERVAL-RELATIONS** - An INTERVAL-RELATION synchronizes the occurrence of two TIME-INTERVALS (e.g., two ACTIVITIES). It specifies an ordering with respect to the respective START-TIMES and/or END-TIMES of the two related intervals, and the relation may be quantified by a metric LOWER-BOUND and UPPER-BOUND on the temporal separation between ordered TIME-POINTS. An unquantified INTERVAL-RELATION is interpreted as having LOWER-

BOUND, UPPER-BOUND values of $0, \infty$. The set of INTERVAL-RELATIONS includes:

i. **BEFORE** - For two intervals I_1 and I_2, I_1 BEFORE $I_2[lb, ub]$ implies that:
   A. $Start\_Time(I_2) \geq End\_Time(I_1) + lb$
   B. $Start\_Time(I_2) \leq End\_Time(I_1) + ub$.

ii. **STARTS-BEFORE** - For two intervals I_1 and I_2, I_1 STARTS-BEFORE $I_2[lb, ub]$ implies that:
   A. $Sart\_Time(I_2) \geq Sart\_Time(I_1) + lb$
   B. $Start\_Time(I_2) \leq Start\_Time(I_1) + ub$

iii. **ENDS-BEFORE** - For two intervals I_1 and I_2, I_1 ENDS-BEFORE $I_2[lb, ub]$ implies that:
   A. $End\_Time(I_2) \geq End\_Time(I_1) + lb$
   B. $End\_Time(I_2) \leq End\_Time(I_1) + ub$.

iv. **CONTAINS** - For two intervals I_1 and I_2, I_1 CONTAINS $I_2[lb_1, ub_1, lb_2, ub_2]$ implies that:
   A. $Start\_Time(I_2) \geq Start\_Time(I_1) + lb_1$
   B. $Start\_Time(I_2) \leq Start\_Time(I_1) + ub_1$
   C. $End\_Time(I_1) \geq End\_Time(I_2) + lb_2$
   D. $End\_Time(I_1) \leq End\_Time(I_2) + ub_2$.

v. **SAME-START** - For two intervals I_1 and I_2, I_1 SAME-START $I_2[lb, ub]$ implies that:
   A. $|Start\_Time(I_2) - Start\_Time(I_1)| \leq ub$.

vi. **SAME-END** - For two intervals I_1 and I_2, I_1 SAME-END $I_2[lb, ub]$ implies that:
   A. $|End\_Time(I_2) - End\_Time(I_1)| \leq ub$.

The SAME-END relation can be specialized to define a **MARRY-UP TIME CONSTRAINT** on ACTIVITIES that are transporting CARGO that must later be joined (as for example is required to maintain UNIT INTEGRITY). In this case, the ub (or MAXIMUM SEPARATION parameter) is the MARRY-UP-WINDOW specified in the associated MOVEMENT REQUIREMENT.

(b) **DURATION-CONSTRAINTS** - A DURATION-CONSTRAINT imposes a LOWER-BOUND or UPPER-BOUND (or both) on the separation between the START and END points of a given TIME-INTERVAL. For interval I_1 and $[lb, ub], lb \leq ET(I_1) - ST(I_1) \leq ub$. An ACTIVITY-DURATION and a RESOURCE'S SETUP-DURATION are two previously mentioned types of DURATION-CONSTRAINTS.

WORLD CONDITIONS

WORLD-CONDITIONS specify conditions that must hold in the current WORLD-STATE for an ACTIVITY to feasibly execute. A WORLD CONDITION is defined with respect to some dynamic (i.e., time varying) property of the WORLD STATE. A WORLD CONDITION can be satisfied in one of two ways: (1) the ACTIVITY requesting the condition can be constrained to occur in an interval of time in which the CONDITION is known to hold, or (2) if there is no feasible interval in the current WORLD STATE, an additional ACTIVITY (or ACTIVITY NETWORK) which brings about the desired condition can be instantiated.

WORLD-CONDITIONS can be categorized according the type of dynamic property of interest. Two common subtypes relate to the AVAILABLE-CAPACITY of RESOURCES and the CURRENT LOCATION of MOBILE ENTITIES:

1. **RESOURCE-REQUIREMENTS** define a class of WORLD CONDITION that relates specifically to the availability of RESOURCES and RESOURCE CAPACITY over time. As previously discussed, resources provide capacity that is allocated to support execution of activities, and the AVAILABLE CAPACITY of a RESOURCE is one important dynamic property of the WORLD STATE. A RESOURCE REQUIREMENT for an ACTIVITY a specifies that some amount of CAPACITY of a RESOURCE r that must be available during the execution of the ACTIVITY in order for the r to be feasibly assigned to a. Some examples of RESOURCE REQUIREMENTS in the transportation planning and scheduling domain include:

   - **AVAILABLE LIFT CAPACITY** - This requirement states that the AVAILABLE CAPACITY of the CARRIER resource that is assigned to a TRANSPORT ACTIVITY must be $\geq$ the QUANTITY of CARGO specified in the associated MOVEMENT REQUIREMENT and of the same type as the CARGO TYPE specified in the MOVEMENT REQUIREMENT.
   - **AVAILABLE ON-LOAD (OFFLOAD) CAPACITY** - This requirement states that there must be an available GROUND CREW during ON-LOAD (OFFLOAD) of a given vehicle.

2. **LOCATION REQUIREMENTS** are WORLD CONDITIONS that refer to the (desired) LOCATION of a MOBILE OBJECT. In the transportation planning and scheduling domain, examples include:

   - **LIFTER AT ORIGIN** and **LIFTER AT DESTINATION** - the CARRIER resource of a TRANSPORT-ACTIVITY a must be at the ORIGIN LOCATION of a for the duration of its ON-LOAD (sub)activity, and execution of a will leave the CARRIER resource at a's DESTINATION when it completes.

- **C5 CARGO HANDLER AT ORIGIN (DESTINATION)** - A CARRIER resource R might have additional USAGE RESTRICTIONS relating to the presence of other supporting resources at specific LOCATIONS. In this case, a C5 AIRCRAFT requires special C5 CARGO HANDLING EQUIPMENT to on-load and offload CARGO.
- **CARGO AT DESTINATION** - This is high level ACHIEVEMENT CONDITION associated with any type of TRANSPORT SERVICE that a MOVEMENT REQUIREMENT requests.

CONJUNCTIVE CONSTRAINTS

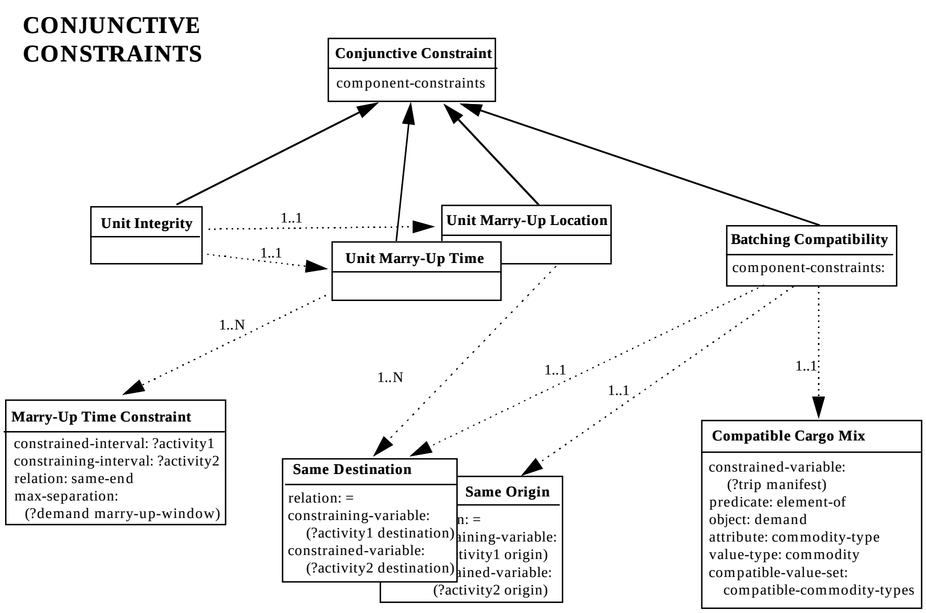

Figure 5.17: Conjunctive Constraints

The concept of a CONJUNCTIVE CONSTRAINT allows the composition of more complex constraints from basic components. Specifically, a CONJUNCTIVE CONSTRAINT is composed of a set of COMPONENT CONSTRAINTS, each of which can be either basic or itself a conjunctive constraint. A CONJUNCTIVE CONSTRAINT is satisfied if each of its COMPONENT CONSTRAINTS is satisfied.

Figure 5.17 provides two representative examples of CONJUNCTIVE CONSTRAINTS from the transportation planning and scheduling domain:

- **UNIT INTEGRITY** - UNIT INTEGRITY is a constraint which requires elements of a given UNIT to maintain a certain degree of temporal and spatial proximity to one another while in transit from some ORIGIN to some DESTINATION.

- **BATCHING COMPATIBILITY** - A BATCHING COMPATIBILITY defines the conditions under which CARGO from different MOVEMENT REQUIREMENTS can be grouped together on the same trip. As defined in Figure 5.17, batchable CARGO must be traveling from the SAME ORIGIN to the SAME DESTINATION and the respective COMMODITY TYPES must be compatible. For example, the COMMODITY-TYPE AMMUNITION has very few COMPATIBLE COMMODITY TYPES.

5.6.2 Properties.

A CONSTRAINT may be considered to be **HARD** or **SOFT**. The problem solver is never allowed to violate HARD-CONSTRAINTS. SOFT-CONSTRAINTS, alternatively, are considered to be **RELAXABLE** if need be. For example, DUE-DATE-CONSTRAINTS are treated as RELAXABLE-CONSTRAINTS in many scheduling contexts. The designation of RELAXABLE-CONSTRAINTS is typically accompanied by a specification of **OBJECTIVE CRITERIA** or **PREFERENCES**. When due dates can be relaxed, for example, minimizing tardiness is a common OBJECTIVE CRITERION. OBJECTIVE CRITERIA and PREFERENCES prioritize the space of possible RELAXATIONS of a CONSTRAINT and provide a basis for measuring solution quality.

Chapter 6

Concluding Remarks

In this report, we have developed a domain ontology for transportation planning and scheduling, with particular emphasis on the concerns of the multi-modal problem faced by US TRANSCOM. An examination of a number of contemporary ontology and common plan representation development efforts vis a vis the requirements of this and other transportation planning and scheduling problems led us to adopt the OZONE scheduling ontology as a starting point, and to extend this core ontology with activity and plan modeling concepts taken from other ontology efforts. This ontological base was used to elaborate basic concepts of the transportation planning and scheduling domain, including MOVEMENT REQUIREMENTS, TRANSPORT SERVICES, TRANSPORT ACTIVITIES, TRANSPORT RESOURCES and transportation planning and scheduling CONSTRAINTS. In elaborating these basic concepts, we have defined a fairly large base of transportation planning and scheduling terms. However, our principal goal has not been to produce an exhaustive domain ontology, but rather to define a representational framework and ontological basis for comprehensive modeling and solution of multi-modal transportation planning and scheduling problems.

Chapter 7

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