Working with UML:
A Software Design Process Based on Inspections for the Unified Modeling Language

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1. Introduction

This text describes a simple and effective Object Oriented software design process template having UML as the modeling language and extensively using inspections to support the construction and maintenance of software products. Besides, a survey of specific literature regarding UML and Object Oriented paradigm is presented along the text. This software design process uses a sequential organization based on the waterfall approach for two reasons: to help with the explanation of design activities in the context of this text and to make available a standard process that can be continuously improved by developers. This process does not result in a loss of generality in this discussion because after developers understand the process they have freedom to reorganize all of the component phases. The activities that were considered for such a software process template are requirements specification, high and low level design, coding and testing. However, we have inserted inspection activities at various points in the lifecycle to help address quality issues, as explained in section 3.3.1.

We have concentrated on describing only activities that specifically use the OO paradigm and make use of UML. So, elicitation of requirements (Leite and Freeman, 1991), an important task in the context of software development, is not considered here in detail. Different techniques and methods can be used for requirements elicitation and description (Finkelstein et al., 1994). Requirements descriptions are paradigm-independent and must be chosen based on customer needs (IEEE, 1993). System scenario descriptions (use-cases) are part of the requirements specification and are produced after the problem is described. We consider this as part of the OO design, because the way that scenarios are described can impact future design solutions. Use cases are a good mechanism to help identify basic concepts and give an indication of the functionality of the system. The functional requirements and problem domain concepts described by the requirements and use cases arrange the information used to produce the high level design, a set of UML artifacts. Then, these design artifacts are evolved to include non-functional requirements and the features that deal with the computational side of the problem, or the solution domain. These evolved artifacts are the low-level design. The result of this process will be a set of models ready for coding and testing.

Generally, a software development process defines the way real world concepts should be represented, interpreted and transformed into a working software system. Typically, the software development process is guided by a strategy or paradigm. There are some paradigms, such as

structured (or functional) and data-oriented (Pfleeger, 1998) that are well established. Although these paradigms can be used to specify and design systems for different types of problems, their use impacts the quality and productivity of software development. In these paradigms, developers do not use a consistent notation throughout the software lifecycle. This reduces their freedom to reorganize these activities to fit the software life cycle models of their organization. The Object-Oriented (OO) paradigm has emerged to address such issues. Although no "perfect" development paradigm exists (since effective software development also addresses issues beyond tailoring the software process), the OO paradigm has demonstrated its capability for supporting software process improvements in situations where other models were not suitable (Lockman and Salasin, 1990). The OO paradigm's use of the logical constructs (Meyer, 1997) of class, object, inheritance, polymorphism, aggregation, composition and message to describe concepts and build artifacts across the software life-cycle improves the software process, because it:

1) Allows developers to use a consistent notation with a common set of constructs across phases, increasing their communication throughout different development phases;
2) Deals with well-defined components, protected by encapsulation (data and functionality) and displaying their corresponding interfaces, which allows the organization of the development activities using different software life-cycle models (Pressman, 1997), and;
3) Can be used as a criterion to identify possible parallel development tasks, speeding up the full development process.

OO Design is a set of activities (scenario description, high and low level design) concerned with the representation of real world concepts (as described by the requirement descriptions) as a collection of discrete objects that incorporate both data structure and behavior. These concepts must be somehow extracted from the requirements[1] to guide the construction of the artifacts that represent system scenarios, and high and low level design (Jalote, 1997).

The technical literature describes several OO notations. A notation when associated with a software development process is called a methodology. For instance, methodologies such as

[1] Requirements can be specified using a number of notations, from natural language to formal specifications. In the context of this work we consider that requirements are organized and described using natural language. It does not result in any loss of generality of our discussion, since OO design is concerned with translating the meaning of system requirements regardless of their notation.

OMT (Rumbaugh et al., 1992), BOOCH (1994), OOSE (Jacobson et al., 1992), FUSION (Coleman et al., 1993) have been suggested. All of these methodologies are based on a specific software development process and use their own syntax and notation in trying to define a broad-spectrum software development methodology. However, it is not easy to define a software development methodology, which is general enough to fit all software development contexts and domains. Each of these methodologies is suitable for specific systems (or problem domains), but not for all systems. Because different methodologies use different design representations it is difficult to compare information among projects that used different methodologies, even if those projects are from the same problem domain. These kinds of difficulties can be avoided by using a homogeneous notation (modeling language) and a standard software design process.

One of the perceived benefits of the Object-Oriented paradigm is that developers can use it for different software processes and life cycles. Regardless of the paradigm and the software life cycle used to plan the software process a common set of activities is present, namely requirements specification, design (including high and low level issues), coding and testing. Using this basic set of activities a template for OO design can be created, showing how the activities can be represented using a homogenous notation. Additionally, (Kitchenham et al., 1999) argued that software maintenance processes are similar to software development processes, which makes this template with slight modification also suitable to software evolution and maintenance.

Developers can tailor this software process to their specific development context while continuing to use the same modeling language. These modeling languages represent an interesting way of using OO constructs to describe problem domain concepts. By providing graphical representation for these constructs, these languages simplify the representation and allow developers to highlight important information about the problem domain. Moreover, they provide a well-specified and homogenous set of constructs to capture the different object perspectives (static and dynamic) making the representation of the information consistent and reusable across different projects.

The Unified Modeling Language (UML) is an example of such a language. Several companies and organizations around the world have used it and it has been adopted as an Object Management Group (OMG) standard (OMG, 1999). Developers are using UML for more than just representing design diagrams. Several tasks concerned with software architecture modeling

(Conallen, 1999), pattern descriptions (Larsen, 1999), design formalization (Shroff and France, 1997), measurement supporting (Uemura et al., 1998) and OO software inspection (Travassos et al., 1999) have been accomplished using UML artifacts or extended UML artifacts. UML can also be used to represent high-level abstraction concepts, such as software process models (Jäger et al., 1999), meta models (Evans and Kent, 1999) and domain analysis models (Morisio et al., 2000) or physical concepts, such as resources (Selic, 2000) and correlated engineers fields (Epstein and Sandhu, 1999).

UML does not have a software process associated with it. Several software life cycles and processes using UML exist for different contexts and domain applications. Some software process models can be used as frameworks to organize and configure design activities. A few examples are Catalysis (D'Souza and Wills, 1998), RUP (Krutchen, 1999), Unified Software Process (Jacobson et al., 1999) and Open (Graham et al., 1997). Although strong, most of these models impose a high cost, as they are based on automated tools and require some training and detailed planning. Moreover, their weakness in providing techniques or guidance for defect detection in artifacts and the difficulty of adapting them to specific classes of problems, such as e-commerce or real-time systems, make the decision of whether to adopt them a complicated and risky task.

This text has 6 sections including this introduction. Section 2 deals with a short description of UML and how the artifacts are classified. Section 3 describes the design activities and a process for applying them. In section 4 a small example is described and used to illustrate the use of UML, including requirements, high level and some of the low level design issues. In section 5, maintenance is considered along with proposals on how the basic development process discussed in section 3 can be modified to support software evolution and maintenance. Section 6 concludes this text.

2. The Unified Modeling Language (UML)

In recent years, the use of the OO paradigm to support systems development and maintenance has grown. Unlike other paradigms, such as structured or data-oriented development where developers are able to use several different methodologies and notations (Pressman, 1997), the unification of different techniques provided a standard way to represent the software artifacts. One of these standards, representing a notation and modeling language, used by several companies and developers around the world is UML – The Unified Modeling

Language. As stated in (Booch, 1999), “the UML has found widespread use: it has been applied successfully to build systems for tasks as diverse as e-commerce, command and control, computer games, medical electronics, banking, insurance, telephony, robotics, and avionics.”

In 1995, the first UML proposal was produced by combining work by Grady Booch (1994) and James Rumbaugh (1992) and released as version 0.8. Subsequently, Ivar Jacobson's contributions (Jacobson et al., 1992) were integrated into releases 0.9 and 0.91 in 1996. Since then, developers and companies around the world have been working together on its improvement. By integrating different techniques and mechanisms proven effective on industrial projects, the draft evolved through multiple version. These efforts resulted in the development of UML 1.1, which was added to the list of technologies adopted by the Object Management Group (OMG) in November of 1997. OMG has assumed the responsibility of organizing the continued evolution of the standard (Kobryn, 1999). In this text the OMG UML standard version 1.3, released in 1999, has been used (OMG, 1999).

Four objectives guided the development of UML (OMG, 1999) and are reflected in version 1.3:

1) Enable the modeling of systems (and not just software) using object-oriented concepts

The UML artifacts explore basic software development concepts, such as abstraction, information hiding and hierarchy as well as object oriented paradigm constructs, such as class, inheritance, composition and polymorphism (Meyer, 1997). Additionally, it provides techniques to support development, organization, and packaging, and mechanisms to represent the software architecture and deployable components. These features cover different aspects of software development and enable UML to represent not only systems but also software models.

2) Establish an explicit coupling to conceptual as well as executable artifacts

By describing the problem using different perspectives (e.g. static and dynamic views), UML allows developers to capture all the relationships and information structures as well as all the behaviors and object state modifications. Also, specific object constraints and features can be formalized and explicitly connected to the concepts, making the models reliable and able to be verified and validated.

3) Address the issues of scale inherent in complex, mission-critical systems

Because UML does not have standard techniques and processes and can be used in different approaches (top-down and bottom-up) engineers are able to deal with different level of abstraction and formalism, which is required when modeling and building software for different application domains. Moreover, the syntax of the modeling language makes available a homogeneous set of constructs supported by a well-defined set of techniques and that can be organized throughout the software development process to break down and reduce problem representation complexity.

4) Create a modeling language usable by both humans and machines

Although the intention is not to provide a standard framework to implement and integrate CASE tools, UML guarantees the same semantics and understanding for its constructs. This normalization of the representation plays an important role when developers are recognizing and describing problem domains, allowing the same information to be interpreted by different developers. It also stimulates different vendors to provide CASE tools for supporting the language, by defining a consistent and standard set of models to specify and build integration mechanisms for sharing information among different tools.

This section will not discuss all the definitions of UML and its possible uses. Instead, it gives an overview about the different artifacts that can be created and the relationships among them. In section 4, concepts and artifacts will be used to build an example application. The reader who desires a more complete view of UML may find some of the following works useful: An introductory text about UML can be found in (Fowler and Scott, 2000). It describes basic concepts and gives small examples on how the artifacts can be used to represent different projects situations. Rumbaugh (Rumbaugh et al., 1999) prepared a UML reference manual and Booch (Booch et al., 1999) developed a tutorial describing how developers can use UML while performing different design activities. However, if more information is still necessary, the complete set of definitions and formalized concepts can be found in (OMG, 1999). Object oriented concepts and definitions can be found in (Booch, 1994) and (Meyer, 1997).

2.1 Different Perspectives to Improve Design Modeling

Although UML artifacts can be classified in different ways (e.g. the UML draft 1.3 describes the different types of documents, including use case diagrams, class diagrams, behavior diagrams and implementation diagrams) this text classifies UML software artifacts into three general categories: Static, Dynamic and Descriptive. There is a strong connection among

these three categories. Each one of them captures or represents a different system perspective. In this way they are complementary; each describing a specific aspect of a system and together describing all relevant points of view. The classification of these is summarized in Table 2.1.

Category	Artifacts
Static	Class, package, component and deployment diagrams
Dynamic	Use-cases, Interaction (sequence, collaboration), statecharts and activities diagrams
Descriptive	Class descriptions and OCL

Table 2.1 - UML artifact categories

Static artifacts capture the information that is constant for one version of the software or system. This information is always true regardless of the functionality and state of the system. It includes classes, their structural organization (attributes and behaviors) and interface (visibility of behaviors), relationships with other classes (inheritance, aggregations, generalizations and acquaintances) and interdependent packages. Moreover, the physical structure and organization of the software or system, including the components and processors that developers identified during implementation, can be classified as static.

Artifacts that represent the static information are the class, package, component and deployment diagrams. By representing all the relationships among classes and pieces of the system, developers are able to visualize important features of the model, such as interdependence, that will cause the coupling and structural complexity of the model to increase, impacting the cost and quality of the whole design.

Dynamic artifacts describe information about with the communication (message exchanging) among objects and how these objects can be put together to accomplish some service or functionality. Important events in the problem can lead objects to change their states and need to be represented. These state changes can determine the correct behaviors, services and even functionalities that must be performed based on the different scenarios that have been modeled.

The dynamic artifacts are use cases, interaction (sequence and collaboration diagrams), statecharts and activities diagrams. These artifacts enhance the problem description represented in the static view. While static information represents "who" will take part of the solution, dynamic information describes "when". However, the symbiosis between static and dynamic views still is not enough to describe all the details developers need.

Descriptive artifacts describe some of the concepts that can not be represented by static and dynamic artifacts or need a better formalization. They are classified as descriptive because,

regardless of the formalism, they use basically a textual format to describe the concepts. The class descriptions, which are similar to data dictionaries of conventional methods, are an example of this type of artifact. They contain complimentary information about artifacts and the formalization for some of the objects features (e.g. constraints, conditions, assertives) using the object constraint language -OCL (Warmer and Kleppe, 1999).

Although all these artifacts can be produced during design, UML does not impose any order or precedence among them. Rather, developers have the freedom to decide the most affordable configuration. Descriptive artifacts are normally used with the other diagrams to support the description of information represented in the different perspectives. The following section shows a design process that can be used to build UML artifacts. Readers can find further information and examples for all of these artifacts in section 4.

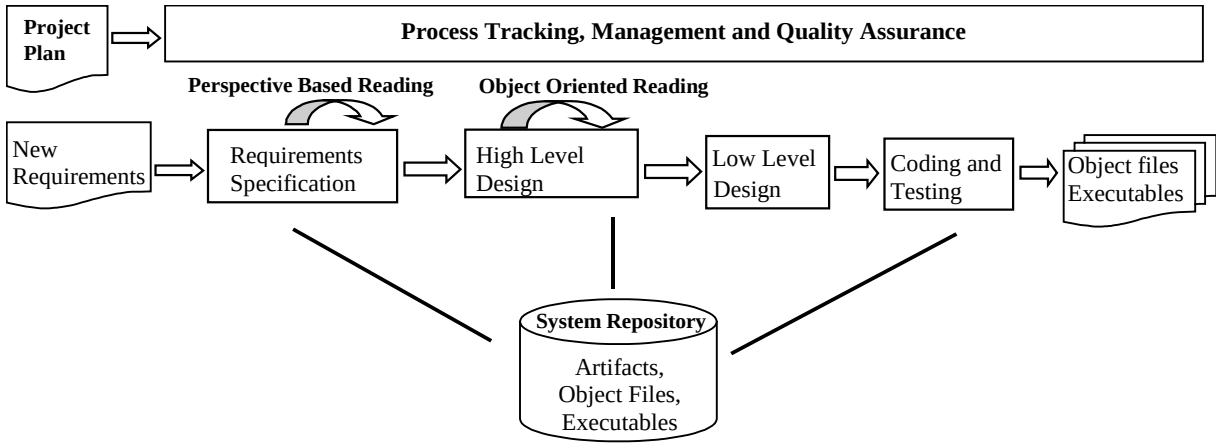

Figure 3.1 – The basic Software Life Cycle

3. Software Process Activities

A framework for the basic software life cycle using UML is shown in Figure 3.1. The process begins with a set of requirements for a new system and ends when the executable files exist. In between, the process proceeds through a number of activities, represented here by rectangles. The horizontal arrows show the sequence of development activities and curved arrows represent inspections, in which the software artifact being produced during a specific activity is reviewed and potentially improved before the next activity can begin[2]. Throughout the life cycle, process tracking, management and quality assurance activities proceed in parallel with

[2] Although inspections are applicable at many stages of the lifecycle, in this text we will concentrate on two phases in particular: requirements and high level design.

development activities, as determined by the project plan. This figure shows the information produced throughout the software life cycle being stored in a repository, which we recommend to allow for the reusing this information.

In this section, we look in more detail at the process activities involved in the high- and low-level design activities, drawing connections where relevant to the other activities in the lifecycle that influence, or are influenced by, the design.

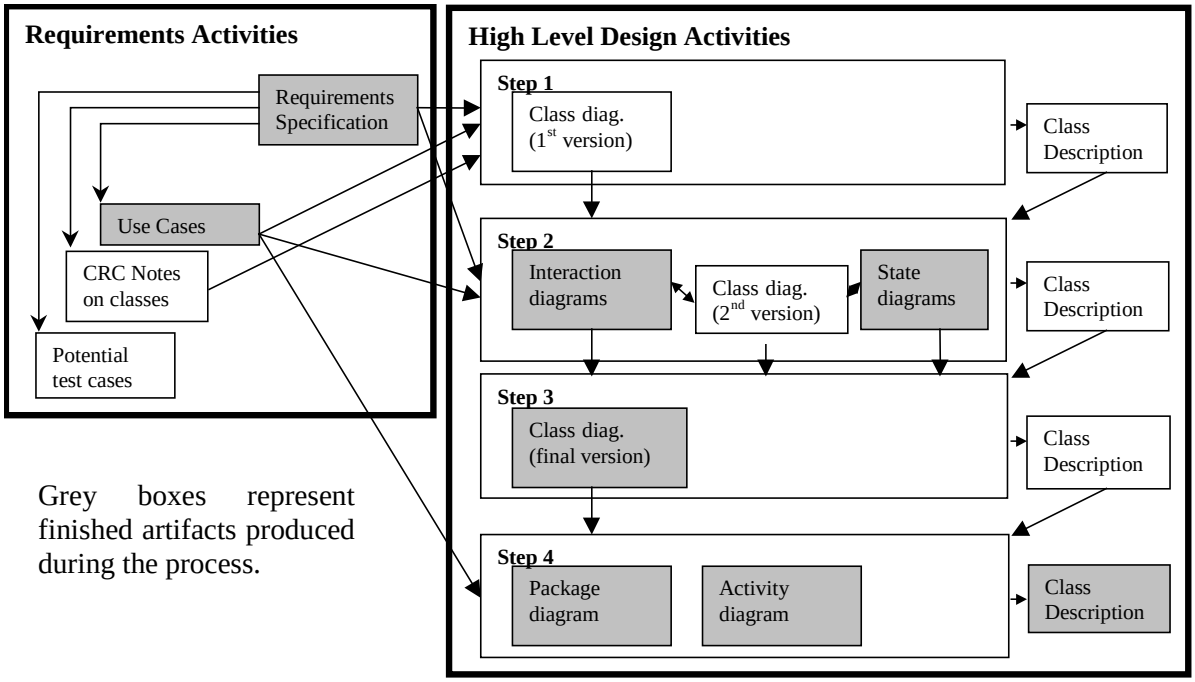

Figure 3.2: High-level design activities, using artifacts created during the requirements phase and during PBR requirements inspections.

3.1 Development Activities

Entire books have been written describing development processes that use UML. Some recommended examples are (D'Souza and Wills, 1998), (Eriksson and Penker, 1997), (Douglass, 1999) and (Jacobson, 1999). In this chapter, we describe a high-level outline of the process, identifying important design steps and dependencies between artifacts. Our goal is not to provide a complete and definitive lifecycle process, but to enable the reader to understand the various process dependencies in sufficient detail that they can reorganize the activities, if desired, into a development process that suits their environment.

Figure 3.2 represents the activities within and leading up to High-Level Design (HLD). Before HLD can begin a set of requirements, at some level of detail, using some notation is

produced during the requirements phase. We recommend the use of a requirements inspection, before beginning HLD, to ensure that the requirements specified are as correct and complete as possible, and adequately represent the needs of the customer. Although a choice of inspection methods exists, Figure 3.2 illustrates the use of PBR, a particular approach to performing requirements inspections in which reviewers produce initial artifacts as they look for requirements defects from different points of view. (PBR is described in more detail in Section 3.2.2.) Using PBR has the advantage of producing an initial set of test cases, which can be used later in the lifecycle, and some information about potential classes, which leads into HLD activities. PBR also produces a representation of system functionalities, which contain important information for HLD. In this example, we have chosen use cases as a functional representation, although other choices are possible. In other environments, use cases can be produced without PBR, and indeed may be the only representation used for specifying requirements.

HLD activities themselves typically begin with the creation of a first draft of the class diagram. Based on an understanding of the requirements, the designers first identify candidate classes in the design space, i.e. the important real-world entities and their associated behaviors, that should be modeled by the system in order to solve the problem specified in the requirements. Use cases also contain important information for identifying potential classes since they help identify the set of functionality of the system, and the actors and other systems that participate in it. A process such as CRC cards (Wirfs-Brock et al., 1990) may be used (either as part of the PBR inspections or as a separate design activity) to start the process. It is important not to engage in over-analysis at this point, as classes will almost surely be discarded, added, or modified over time as the domain is better understood. At this step of the design, as in others, the class description is continually changed to reflect changes in the way the classes themselves are defined.

The next set of activities (step 2 in Figure 3.2) is to construct the interaction and state diagrams, describing in more detail the behavior of the classes (as identified in the class diagram) to achieve the system functionality (as described in the requirements specification and use cases). While accomplishing this, the designer typically gains new insights about the set of necessary classes and their internal structures. Thus a new version of the class diagram is produced (step 3) as the classes are updated with information about their dynamic behaviors.

As a last step, the class diagram is scrutinized with an eye to implementation. If the diagram is large enough that describing an overall implementation approach is unwieldy, it may be divided into packages that reflect the logical groupings of the system classes, allowing it to be broken into chunks for easier communication and planning. Similarly, activity diagrams may be created, using the use cases to suggest the high-level business processes in the system to provide a more concise overview of system functionality.

At the end of HLD, a set of artifacts has been produced (consisting of the class description and class, interaction, and state diagrams, and possibly including package and activity diagrams) that describes the real-world entities from the problem domain. An inspection of the HLD is recommended at this point in the process to ensure that developers have adequately understood the problem before defining the solution. (That is, the emphasis of the inspection should be on high-level comprehension rather than low-level details of the architecture.) Since low-level designs use the same basic diagram set as the high-level design, but adding more detail, reviews of this kind can help ensure that low-level design starts from a high-quality base. To provide a concrete discussion of the inspection process, we introduce OORT inspections, described further in Section 3.2.2. Unlike PBR, OORT inspections do not produce new artifacts, but result solely in updated versions of the existing HLD artifacts.

These HLD artifacts are further refined in Low Level Design (LLD), in which details regarding system implementation are added. The first step of LLD is to adjust the set of design artifacts to the implementation domain. It is at this point that classes are introduced into the model that represents entities in the software-based solution but not the real world, such as abstract data types or screen displays. New methods and attributes may be introduced that reflect how objects will communicate with one another in the programming language chosen, not how high-level messages will be exchanged to achieve the solution.

A second step is to design the system's specific interfaces, such as user interfaces and database solutions (if necessary). Also at this stage, an approach to task management is defined. Any changes necessary to the system classes in order to use these interfaces are reflected in the class description, which is used as input to the next step, in which all of the design artifacts are updated to be consistent with the new implementation details and interfaces specified.

Based on these updated artifacts, a number of final activities are undertaken before coding starts, such as developing a test plan and undertaking coding preparation.

3.2 Quality Assurance and Verification and Validation Activities

Verification and validation (V&V) activities check whether the system being developed can meet the requirements of the customer. To do this, a typical V&V activity focuses on some artifacts produced during the software lifecycle to ascertain if they are correct in themselves (*verification*) and accurately describe the system that should be produced (*validation*). V&V activities are often known as "quality assurance" activities since they are concerned with ensuring the quality of the system being developed, either directly by evaluating the system itself, or indirectly by evaluating the quality of the intermediate artifacts used to produce the system (Pressman, 1997).

At a high level, there are three types of V&V activities. *Measurement* activities attempt to assess the quality of a design by assessing certain structural characteristics. The challenge lies in finding appropriate and feasible metrics for the qualities of interest. For example, designers might be interested in evaluating the modifiability of their design, perhaps because several later versions of the system are expected and it would be worthwhile to minimize the effort required for maintenance in each case. A quality attribute such as this one cannot be measured directly, so the designers instead might choose to measure some other attribute that is measurable and yet provides some insight into the ease of making modifications. Using product metrics in this way requires some kind of baseline data or heuristic information, so that the resulting values can be evaluated. Measurement in the UML/OO paradigm is discussed in Section 3.2.1.

In contrast, inspection and testing, two other V&V activities, attempt to ensure software quality by finding defects from various artifacts produced during the lifecycle. *Inspection* activities require humans to review an artifact and think about whether it is of sufficient quality to support the development of a quality system. There are different types of inspection techniques that represent different strategies for organizing people's roles during the inspections for keeping reviewers focused on the important aspects of the artifact they are inspecting. Inspections are discussed in more detail in section 3.2.2, in which the discussion is illustrated by two specific inspection approaches: Perspective-Based Reading, which is tailored to inspections of requirements documents, and Object-Oriented Reading Techniques, which are tailored for OO design inspections.

Testing is a V&V activity that is appropriate for evaluating software artifacts for which some dynamic behavior or structural feature can be studied. Testing attempts to understand the

quality of the artifact, for instance, by comparing the observed behavior to that which is expected. Typically, testing is applied to code, which can of course be compiled or interpreted and run directly. However, testing can also be applied to other artifacts; for example, requirements and design represented in a formal language can be "run" using simulation and the results studied (Cangussu et al., 1995). In this discussion, we will confine ourselves to discussing code testing and how it can be affected by design decisions. In Section 3.2.3, we will also look briefly at some of the different types of testing techniques that face particular challenges in the OO/UML paradigm.

These different types of V&V activities are not in competition. Rather, some combination is necessary for the production of quality software. Unfortunately, too often development efforts rely entirely on code testing and do not invest in other V&V activities, notably inspections, on artifacts earlier in the lifecycle. Relying exclusively on testing in this way means that defects are not found until the end of the lifecycle, when they are most expensive to fix. Additionally, over-reliance on testing often feeds a tendency of developers to pay less attention to careful design and code production (on the assumption that testing will catch any of the resulting problems). Such an approach can lead to difficulties since it is rarely possible to "test in" quality; low-quality code with multiple patches does not often end up being high-quality code in the end (Perry, 2000). In contrast, augmenting testing with other V&V activities earlier in the lifecycle means that misconceptions about the system can be caught early. For example, requirements inspections can help identify problems with the way a planned system would address customer needs before an inappropriate design has been created. Design inspections can identify problems with the system architecture or design before significant effort has been invested in coding, which may have to be redone if problems are detected later. Inspections cannot replace testing but are an investment that helps "build-in" quality from the beginning and avoid later rework.

Defects in Software Artifacts. Both inspection and testing have the same goal: to find defects in the particular software artifact under review. To get an operational definition of what exactly a "defect" is, we introduce some terms based on the IEEE standard terminology (IEEE, 1987):

- An *error* is a defect in the human thought process made while trying to understand given information, to solve problems, or to use methods and tools. In the context of software

design, an error is a basic misconception concerning how the system should be designed to meet the needs of a user or customer.

- A *fault* is a concrete manifestation of an error within a software artifact. One error may cause several faults and various errors may cause identical faults.
- A *failure* is a departure of the operational software system behavior from user expected requirements. A particular failure may be caused by several faults and some faults may never cause a failure.

For the sake of convenience, we will use the term *defect* as a generic term, to refer to a fault or failure. However, it should be clear that when we discuss the defects found by software inspections, we are really referring to faults. A fault in some static artifact, such as a system design, is important insofar as it can lead to a system implementation in which failures occur. Defects found by testing, on the other hand, are always failures of the software that can then be traced back to faults in a software artifact during debugging.

When we look for a precise definition of a defect, capable of guiding a V&V activity, we face the problem that what constitutes a defect is largely situation-dependent. For example, if there are strong performance requirements on a system, then any description of the system that might lead to those performance requirements being unfulfilled contains a defect; however, for other systems with fewer performance constraints the same artifacts could be considered perfectly correct. Similarly, the types of defects we are interested in for a textual requirements document could be very different from what we would look for in a graphical design representation.

We can avoid this difficulty by identifying broad classes of defects and then instantiating those classes for specific circumstances. For our own work on developing inspection processes, we have found a useful classification that is based on the idea of the software development lifecycle as a series of transformations of a system description to increasingly formal notations. For example, we can think of a set of natural-language requirements as a loose description of a system that is transformed into high- and low-level designs, more formal descriptions of the same basic set of functionality. Eventually these designs are translated into code, which is more formal still, but still describes the same set of functionality (hopefully) as was set forth in the original requirements.

So what can go wrong during such transformations? Figure 3.3 presents a simplified view of the problem, in which all of the relevant information has to be carried forward from the previous phase into a new form, and has to be specified in such a way that it can be further refined in the next phase. The ideal case is shown by arrow 1, in which a piece of information from the artifact created in the previous phase of development is correctly translated into its new form in the artifact in the current phase. There is, however, the possibility that necessary information is somehow left out of the new artifact (arrow 2) or translated into the new artifact but in an incorrect form (arrow 3). In the current phase artifact, there is always the possibility that extraneous information has been entered (arrow 4), which could lead to confusion in the further development of the system, or that information has been specified in such a way as to make the document inconsistent with itself (arrow 5). A related possibility is that information has been specified ambiguously, leading to multiple interpretations in the next phase (arrows 6), not all of that may be correct or appropriate[3].

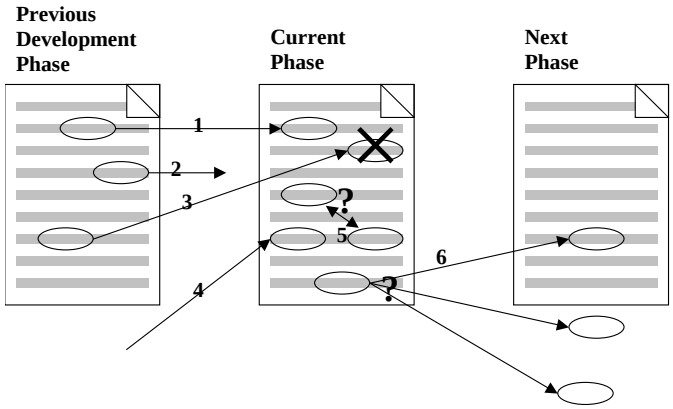

Figure 3.3: Representation of various defect types that can occur during software development.

These generic defect classes can be made more specific, to guide V&V activities for various circumstances. Examples of this are given for specific inspections in Section 3.2.2. Table 3.1 summarizes these defect classes. It is important to note that the classes are not orthogonal (i.e., a particular defect could possibly fit into more than one category) but are intended to give an idea of the set of possible defects that can occur.

[3] Of course, Figure 3.3 is a simplified view. In reality, many of the implied 1-to-1 mappings do not hold. There may be multiple artifacts created in each stage of the lifecycle, and the information in a particular phase can influence *many* aspects of the artifact created in the next phase. For example, one requirement from a requirements specification can impact many components of the system design. When notational differences are taken into account

3.2.1 Measurement

Software development projects desiring some insight into the product being produced and the process being applied use metrics to measure important information about the project. Many companies have full-scale measurement programs that operate alongside software development activities, collecting a standard set of metrics across multiple projects to facilitate the tracking of development progress. The most sophisticated of these use some sort of measurement framework to ensure that the metrics being collected are tied directly to the business goals of the company. For example, the GQM paradigm (van Solingen and Berghout, 1999) makes explicit the connection between overall goals, specific questions that must be answered to achieve the goals, and the metrics that collect information capable of answering the questions.

Defect	***General Description***
Omission	Necessary information about the system has been omitted from the software artifact.
Incorrect Fact	Some information in the software artifact contradicts information in the requirements document or the general domain knowledge.
Inconsistency	Information within one part of the software artifact is inconsistent with other information in the software artifact.
Ambiguity	Information within the software artifact is ambiguous, i.e. any of a number of interpretations may be derived that should not be the prerogative of the developer doing the implementation.
Extraneous Information	Information is provided that is not needed or used.

Table 3.1 – Types of software defects, with generic definitions.

Developers and project managers have found metrics useful for:

- evaluating software quality (e.g. by measuring system reliability),
- understanding the design process (e.g. by measuring how much effort is being spent, and on what activities),
- identifying product problems (e.g. by identifying overly complex modules in the system),
- improving solutions (e.g. by understanding the effectiveness of design techniques and how they can be better tailored to the users), and
- acquiring design knowledge (e.g. by measuring the size of the design being produced).

Two of the most often-measured attributes of an OO design are coupling and cohesion. *Coupling* refers to the degree of interdependence between the parts of a design. One class is

(e.g. textual requirements are translated into a graphical design description) it becomes apparent why performing

coupled to another class when methods declared in one class use methods or attributes of the other class. High coupling in a design can indicate an overly complex or poorly constructed design that will likely be hard to understand. This measure can also indicate potential problems with maintenance since changes to a highly coupled class are likely to impact many other classes in the design. *Cohesion* refers to the internal consistency within parts of the design. Semantically, cohesion is measured by whether there is a logical consistency among the names, methods, and attributes of classes in the design. Syntactically, cohesion can be measured by whether a class has different methods performing different operations on the same set of attributes, which may indicate a certain logical consistency among the methods. A lack of cohesion can also indicate a poorly-constructed design since it implies that classes have methods that would not logically be expected to belong to them, indicating that the domain may not have been modeled correctly and pointing to potential maintenance problems (Coad and Yourdon, 1991).

Size metrics are also used often. Projects undertake size measures for a variety of reasons, such as to produce an estimate of the implementation effort that will be necessary (Clunie et al., 1996). However, no one definitive size metric is possible since each involves some level of abstraction and so may not completely describe all attributes of interest; for example, measuring the number of classes is at best a rough estimate of system size since not all classes are at the same level of complexity. Lorenz and Kidd (1994) identified a number of size metrics for requirements, high- and low-level design:

- Number of Scenarios Scripts (**NSS**): counts the number of use cases that are necessary to describe the system. Since this is a measure of functionality it is correlated to the size of the application and, more directly, to the number of test cases that will be necessary.
- Number of Key Classes (**NKC**): counts the number of domain classes in the HLD, giving a rough estimate of the amount of effort necessary to implement the system and the amount of reuse that will be possible.
- Number of Support Classes (**NSC**): counts the number of classes in the LLD, giving rough predictions of implementation effort and reuse.

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effective inspections can be such a challenging task.

- Average Number of Support Classes per Key Class (**ANSC**): measures the degree of expansion of the system from HLD to LLD, giving an estimate of how much of the system is necessary for implementation-level details.
- Number of Subsystems (**NSUB**): a rough size measure based on larger aggregates of system functionality.
- Class Size (**CS**): for an individual class, this metric is defined as the total number of operations plus the number of attributes (both including inherited features).
- Number of Operations Overridden by a Subclass (**NOO**)
- Number of Operations Added by a Subclass (**NOA**)
- Specialization Index (**SI**): defined as (**NOO** x level in the hierarchy)/(Total methods in the class)

Metrics exist to measure other attributes of designs besides size. Often, these metrics attempt to somehow measure design complexity, on the assumption that more complex designs are harder for human developers to understand and consequently harder to develop and maintain. Perhaps the most well-known of these metrics sets was proposed by Chidamber and Kemerer (1994):

- Weighted Methods per Class (**WMC**): measures a class by summing the complexity measures assigned to each of the class' methods, motivated by the idea that the number and complexity of a class' methods are correlated with the effort required to implement that class. Another use of this metric is suggested by the heuristic that classes with large numbers of methods are likely to be more application specific, and hence candidates for reuse.
- Depth of Inheritance (**DIT**): measures the depth at which a class appears in an inheritance hierarchy. Classes deeper in the hierarchy are likely to inherit a larger number of methods and attributes, making their behavior more difficult to predict.
- Number of Children (**NOC**): measures the number of subclasses that directly inherit from a given class. A high NOC value typically indicates that a class should be tested more extensively, since such classes may represent a misuse of subclassing, but definitely have an extensive influence on the design.
- Coupling Between Objects (**CBO**): measures the number of other classes to which a class is coupled. Extensive coupling indicates higher complexity (and hence suggests more testing is necessary) but also signals a likely difficulty in reusing the class.

- Response for a Class (**RFC**): measures the number of methods belonging to the class that can be executed in response to a message. The higher the value, the more complex testing and debugging of that class are likely to be.
- Lack of Cohesion in Methods (**LCOM**): measures the degree to which the methods of a class make use of the same attributes. More overlap among the attributes used is assumed to signal more cohesiveness among the methods. A lack of cohesion increases complexity, increasing the likelihood of development errors, and typically indicates that this class should be split into two or more subclasses.

The popularity of the Chidamber and Kemerer metrics for describing designs has led to a few extensions to be proposed, so that the range of measures could be tailored to particular needs. For example, Lie and Henry (1993) introduced two new metrics that were useful for the commercial systems (implemented in an OO dialect of Ada) they were studying:

- Message Passing Coupling (**MPC**): calculated as the number of "send" statements defined in a class.
- Data Abstraction Coupling (**DAC**): calculated as the number of abstract data types used in the measured class but defined in another class of the system.

And, Basili, Briand, and Melo (1995) introduced a version of the Chidamber and Kemerer metrics tailored to C++:

- **WMC**: redefined so that all methods have complexity 1 (i.e. the metric is a count of the number of methods in a class) and "friend" operators do not count.
- **DIT**: measures the number of ancestors of a class.
- **NOC**: measures the number of direct descendants for each class.
- **CBO**: redefined so that a class is coupled to another if it uses its member functions and/or attributes.
- **RFC**: measures the number of functions directly invoked by member functions or operators of a class.
- **LCOM**: defined as the number of pairs of member functions without shared instance variables, minus the number of pairs of member functions with shared instance variables.

The Table 3.2 summarizes the metrics discussed in this section and connects them with the lifecycle stages for which they are appropriate.

3.2.2 Inspections

Software inspections are a type of V&V activity that can be performed throughout the software lifecycle. Because they rely on human understanding to detect defects, they have the advantage that they can be done as soon as a software work artifact is written and can be used on a variety of different artifacts and notations. Because they are typically done by a team, they are a useful way of passing technical expertise as to good and bad aspects of software artifacts among the participants. And, because they get developers familiar with the idea of reading each other's artifacts, they can lead to more readable artifacts being produced over time. On the other hand, because they rely on human effort, they are affected by nontechnical issues: reviewers can have different levels of relevant expertise, can get bored if asked to review large artifacts, can have their own feelings about what is or is not important, or can be affected by political or personal issues. For this reason, there has been an emphasis on defining processes that people can use for performing effective inspections.

	Req. Description	**High-Level Design**	**Low-Level Design**	**Coding**	**Testing**
Lorenz & Kidd					
NSS	X				
NKC	X	X			
NSC			X		
ANSC			X		
NSUB			X	X	
CS		X	X	X	
NOO		X	X	X	X
NOA		X	X	X	
SI		X	X	X	X
Chidamber & Kemerer					
WMC		X	X		X
DIT		X	X		X
NOC		X	X		X
CBO			X		X
RFC			X	X	
LCOM			X	X	X

Table 3.2: Metrics discussed in this chapter for each phase of the lifecycle.

Most of the current work on inspections owes a large debt to the very influential works of (Fagan, 1986) and (Gilb and Graham, 1993). In both, the emphasis is on the inspection *method*[4], in which the following phases are identified:

- Planning: In this phase, the scope, artifact, and participants for the inspection are decided. The relevant information and materials are distributed to each inspector, and their responsibilities are explained to them, if necessary.
- Detection: The inspectors review the artifact on their own, identifying defects or other quality issues they encounter.
- Collection: The inspectors meet as a team to discuss the artifact, and any associated problems they feel may exist. A definitive list of the issues raised by the team is collected and turned over to the author of the artifact.
- Correction: The author updates the artifact to reflect the concerns raised by the inspection team.

The methods do not, however, give any guidelines to the reviewer as to how defects should be found in the detection phase; both assume that the individual review of these documents can already be done effectively. Having been the basis for many of the review processes now in place (e.g., at NASA (1993)), (Fagan, 1986) and (Gilb and Graham, 1993) have inspired the direction of much of the research in this area, which has tended to concentrate on improving the review *method*. Proposed improvements to Fagan's method often center on the importance and cost of the meeting. For example, researchers have proposed:

- Introducing additional meetings, such as the root cause analysis meeting of (Gilb and Graham, 1993).
- Eliminating meetings in favor of straightforward data collection (Votta, 1993).

More recent research has tried to understand better the benefits of inspection meetings. Surprisingly, such studies have reported that, while they may have other benefits, inspection meetings do not contribute significantly to the number of defects found (Votta, 1993)(Porter, 1995). That is, team meetings do not appear to provide a significantly more complete list of defects than if the actual meeting had been dispensed with and the union of the individual

[4] In this text we distinguish a "technique" from a "method" as follows: A technique is a series of steps, at some level of detail, that can be followed in sequence to complete a particular task. We use the term "method" as defined in (Basili, 1996), "a management-level description of when and how to apply techniques, which explains not only how to apply a technique, but also under what conditions the technique's application is appropriate."

reviewers' defect lists taken. This line of research suggests that efforts to improve the review *technique*, that is, the process used by each reviewer to find defects in the first place, could be of benefit.

One approach to doing this is provided by *software reading techniques*. A reading technique is a series of steps for the individual analysis of a software product to achieve the understanding needed for a particular task (Basili et al., 1996). Reading techniques increase the effectiveness of *individual* reviewers by providing guidelines that they can use, during the detection phase of a software inspection, to examine (or "read") a given software document and identify defects. Rather than leave reviewers to their own devices reading techniques attempt to capture knowledge about best practices for defect detection into a procedure that can be followed.

In our work we have defined the following goals for inspection techniques:

- *Systematic*: Specific steps of the individual review process should be defined.
- *Focused*: Different reviewers should be asked to focus on different aspects of the document, thus having unique (not redundant) responsibilities.
- Allowing *controlled improvement*: Based on feedback from reviewers, specific aspects of the technique should be able to be identified and improved.
- *Tailorable*: The technique should be customizable to a specific project and/or organization.
- Allows *training*: It should be possible to train the reviewers for applying the technique.

In this section, we look at reading techniques that directly support the production of quality software designs: PBR, which ensures that the artifacts input to HLD are of high quality, and OORTs, which evaluate the quality of the HLD itself.

A Requirements Inspection Technique: Perspective-Based Reading (PBR)

A set of inspection techniques known as Perspective-Based Reading (PBR) was created for the domain of requirements inspections. PBR is designed to help reviewers answer two important questions about the requirements they are inspecting:

- How do I know what information in these requirements is important to check?
- Once I have found the important information, how do I identify defects in that information?

PBR exploits the observation that different information in the requirements is more or less important for the different uses of the document. That is, the ultimate purpose of a

requirements document is to be used by a number of different people to support tasks throughout the development lifecycle. Conceivably, each of those persons finds different aspects of the requirements important for accomplishing his or her task. If we could ask all of the different people who use the requirements to review it from their own point of view, then we would expect that all together they would have reviewed the whole document (since any information in the document is presumably there to help somebody do his or her job).

Thus, in a PBR inspection each reviewer on a team is asked to take the perspective of a specific user of the requirements being reviewed. His or her responsibility is to create a high-level version of the work products that a user of the requirements would have to create as part of his or her normal work activities. For example, in a simple model of the software lifecycle we could expect the requirements document to have three main uses in the software lifecycle:

- As a description of the needs of the *customer*: The requirements describe the set of functionality and performance constraints that must be met by the final system.
- As a basis for the *design* of the system: The system designer has to create a design that can achieve the functionality described by the requirements, within the allowed constraints.
- As a point of comparison for system *test*: The system's test plan has to ensure that the functionality and performance requirements have been correctly implemented.

In such an environment, a PBR inspection of the requirements would ensure that each reviewer evaluated the document from one of those perspectives, creating some model of the requirements to help focus their inspection: an enumeration of the functionality described by the requirements, a high-level design of the system, and a test plan for the system, respectively. The objective is not to duplicate work done at other points of the software development process, but to create *representations* that can be used as a basis for the later creation of more specific work products and that can reveal how well the requirements can support the necessary tasks.

Once reviewers have created relevant representations of the requirements, they still need to determine what defects may exist. To facilitate that task, the PBR techniques provide a set of questions tailored to each step of the procedure for creating the representation. As the reviewer goes through the steps of constructing the representation, he or she is asked to answer a series of questions about the work being done. There is one question for every applicable type of defect. (The defect types, tailored specifically to the requirements phase, are given in Table 3.3.) When the requirements do not provide enough information to answer the questions, this is usually a

good indication that they do not provide enough information to support the user of the requirements, either. This situation should lead to one or more defects being reported so that they can be fixed before the requirements need to be used to support that task later in the product lifecycle.

More information, including example techniques for the three perspectives identified above, is available at http://fc-md.umd.edu/reading/reading.html.

Defect	***Applied to requirements***	***Applied to design***
Omission	(1) some significant requirement related to functionality, performance, design constraints, attributes or external interface is not included; (2) responses of the software to all realizable classes of input data in all realizable classes of situations is not defined; (3) missing sections of the requirements document; (4) missing labeling and referencing of figures, tables, and diagrams; (5) missing definition of terms and units of measures (ANSI, 1984).	One or more design diagrams that should contain some concept from the general requirements or from the requirements document do not contain a representation for that concept.
Incorrect Fact	A requirement asserts a fact that cannot be true under the conditions specified for the system.	A design diagram contains a misrepresentation of a concept described in the general requirements or requirements document.
Inconsistency	Two or more requirements are in conflict with one another.	A representation of a concept in one design diagram disagrees with a representation of the same concept in either the same or another design diagram.
Ambiguity	A requirement has multiple interpretations due to multiple terms for the same characteristic, or multiple meanings of a term in a particular context.	A representation of a concept in the design is unclear, and could cause a user of the document (developer, low-level designer, etc.) to misinterpret or misunderstand the meaning of the concept.
Extraneous Information	Information is provided that is not needed or used.	The design includes information that, while perhaps true, does not apply to this domain and should not be included in the design

Table 3.3 – Types of software defects, with specific definitions for the requirements and design

Design Inspection Techniques: Object-Oriented Reading Techniques (OORTs)

In PBR, reviewers are asked to develop abstractions, from different points of view, of the system described by the requirements because requirements notations do not always facilitate the identification of important information and location of defects by an inspector. For an OO design, in contrast, the abstractions of important information already exist: the information has

already been described in a number of separate models or diagrams (e.g. state machines, class diagrams) as discussed at the end of the previous section.

However, the information in the abstractions has to be checked for defects, and reading techniques can still supply a benefit by providing a procedure for individual inspection of the different diagrams, although unique properties of the OO paradigm must be addressed. In an object-oriented design we have graphical representations of the domain concepts instead of the natural-language representation found in the requirements document. Another feature of object oriented designs that has to be accounted for is the fact that while the different documents within the design all represent the system, they present different views of the information.

A set of Object-Oriented Reading Techniques (OORTs) has been developed for this purpose, focused on a particular set of defects that was defined by tailoring the generic defect definitions from Table 1 to the domain of OO designs (Table 3.3). For example, the information in the artifact must be compared to the general requirements in order to ensure that the system described by the artifact matches the system that is supposed to be built. Similarly, a reviewer of the artifact must also use general domain knowledge to make sure that the artifact describes a system that is meaningful and can be built. At the same time, irrelevant information from other domains should typically be prevented from appearing in the artifact, since it can only hurt clarity. Any artifact should also be analyzed to make sure that it is self-consistent and clear enough to support only one interpretation of the final system.

The PBR techniques for requirements are concerned mainly with checking the correctness of the document itself (making sure the document was internally consistent and clearly expressed, and whether the contents did not contradict any domain knowledge). A major difference in the OORTs is that for checking the correctness of a design, the reading process must be twofold. As in requirements inspection, the correctness and consistency of the design diagrams themselves must of course be verified (through "horizontal reading"[5]) to ensure a consistent document. But a frame of reference is necessary in order to assess design correctness. Thus it is also necessary to verify the consistency between design artifacts and the system

[5] Horizontal reading refers to reading techniques that are used to read documents built in the same software lifecycle phase. (See Figure 3.4.) Consistency among documents is the most important feature here.

requirements (through "vertical reading"[6]), to ensure that the system design is correct with respect to the functional requirements.

The OORTs consist of a family of techniques in which a separate technique has been defined for each set of diagrams that could usefully be compared against each other. For example, sequence diagrams need to be compared to state machines to detect whether, for a specific object, there are events, constraints or data (described in the state machine) that could change the way that messages are sent to it (as specified in the sequence diagram). The advantage of this approach is that a project engaged in design inspections can select from this family only the subset of techniques that correspond to the subset of artifacts they are using, or that are particularly important for a given project. The full set of horizontal and vertical reading techniques is defined as illustrated in Figure 3.4. Each line between the software artifacts represents a reading technique that has been defined to read one against the other.

These techniques have been demonstrated to be feasible and helpful in finding defects (Shull et al., 1999) (Travassos et al., 1999). More information about the OORTs, including a technical report describing how these techniques were defined, is available at http://fc-md.umd.edu/reading/reading.html.

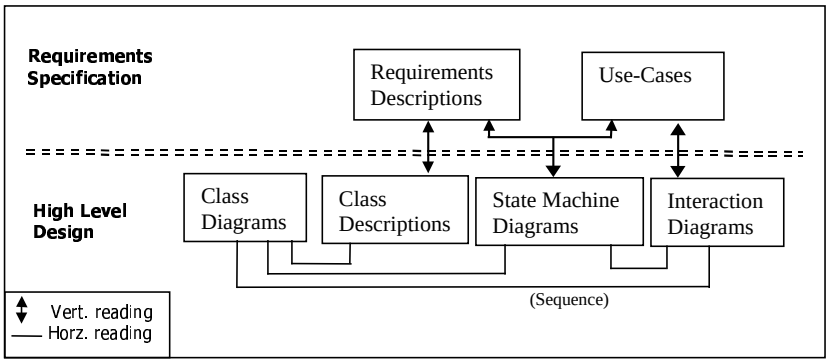


Figure 3.4: The set of OORTs (each arrow represents one technique) that has been defined for various design artifacts.

3.2.3 Testing

Testing is a V&V activity that is performed toward the end of the lifecycle (or, more precisely, toward the end of some iteration through the development process), once executable code has been produced. It is a relatively expensive activity; it typically takes great ingenuity to

[6] Vertical reading refers to reading techniques that are used to read documents built in different software lifecycle phases. (See Figure 3.4.) Traceability between the phases is the most important feature here.

exercise all of the important features of a system under realistic conditions and notice discrepancies from the expected results, not to mention tracing the system failures observed during execution back to the relevant faults in the code. Nevertheless, it remains an essential way of ensuring the quality of the system. Due to this expense, however, exhaustive testing is not feasible in most situations, and so it is important for development projects to have a well thought-out test plan that allocates time and resources in such a way as to provide effective coverage of the system. A number of general testing approaches have been developed and in this section we describe briefly how they map to systems developed using OO/UML and what types of difficulties are introduced by the new paradigm.

A test plan is a general document for the entire project that identifies the scope of the testing effort, the general approach to be taken, and a schedule of testing activities. Regardless of the paradigm by which a system has been developed, a good test plan will also include:

- a test unit specification, listing the modules to be tested and the data used during testing;
- a listing of the features to be tested (possibly including functionality, performance, and design constraints);
- the deliverables resulting from the test activities (which might be a list of the test cases used, detailed testing results, a summary report, and/or data about code coverage);
- personnel allocation, identifying the persons responsible for performing the different activities.

Also independent of the development paradigm are the criteria for a good test plan: effectiveness (ideally, it should result in all of the defects in the product being fixed), a lack of redundancy (effort is spent efficiently), completeness (important features of the system are not missed during testing), and the right level of complexity.

Planning a system-wide test plan should make use of three different test techniques. These techniques are complementary, meaning that no one technique covers all the important aspects of a system; rather, effort should be allocated to testing of each type to a greater or lesser degree, depending on how much it meets the needs of the particular system being developed. These three techniques are:

- Functional (black-box) testing (Beizer, 1995): Test cases are built based on the functionality that has been specified for the system, with the objective of ensuring that the system behaves correctly under all conditions. Because this technique is concerned with the system's

behavior, not implementation, approaches developed for other programming paradigms can be used on OO systems without change, such as equivalence partitioning, boundary value analysis, and cause-effect graphing.

- Structural (white-box) testing (Binder, 1999), (Perry, 2000): Test cases are built based on the internal structure of the software, with the objective of ensuring that all possible execution paths through the code will produce correct results. The nature of OO programming, in which data flow can be distributed among objects, each of which maintains its own separate state, introduces some complexities which are described below, under "unit testing." Structural testing approaches can be based on control flow, data flow, or program complexity. There is ongoing research as to how these approaches can be adapted to OO/UML (Kung et al., 1998) but there are no practical techniques as yet.
- Defect-based testing: Test cases are built to target likely classes of defects. Approaches include defect seeding (in which a set of defects is seeded into the code before testing begins, to get some idea of the effectiveness of the testing activities), mutation testing for unit testing (Offutt, 1995), and interface mutation for integration testing (Delamaro and Maldonado, 1996). Although work has been done on identifying useful classes of defects for use in the testing of structured programs, little has been published as to which types of defects are most useful to focus on in OO development.

Testing usually proceeds through multiple levels of granularity, and techniques from each of the above types may be applied at each level. Testing may proceed from unit testing, in which individual components of the system are tested in isolation, to integration testing, in which components are tested while working together, to system and acceptance testing, in which the system is tested as an operational whole. Development with OO/UML does not change testing at the system level, because the goal there is to test functionality independent of the underlying implementation, but does affect testing at other levels:

- Unit testing: Unit testing is complicated in OO/UML, first and foremost because it is not generally agreed upon what the "unit" should represent. In structured programming, the unit is generally taken to be a code module, but in OO/UML, it can be a method, a class, or some larger aggregation of classes such as a package. Aside from the matter of notation there are still significant technical difficulties. Inheritance and polymorphism introduce challenges because they allow many execution paths to exist that are not easy to identify from inspecting

the class. Additionally, object states cause complications because the different states an object can be in, and how these states affect the responses to messages, must be taken into account during testing.

- Integration testing: No matter how the "unit" is defined, OO systems will typically have a higher number of components, that need to be integrated earlier in the development cycle, than a non-OO system. On top of that, managing integration testing in UML/OO can be quite complex since typically a simple calling tree does not exist; objects do not exist statically throughout the lifetime of the system but are created and deleted while responding to triggering events. Thus the number of interactions between components will be much higher than it would be for a non-OO system. It is important to remember that, for these reasons, some interaction problems will not be apparent until many objects have been implemented and activated, relatively late in the testing process.

4. The Example

This section illustrates how developers can use the previously defined design process to build UML artifacts, by describing the design of an example system. The example explains the development of a hypothetical system for a self-service gas station, from the completion of requirements to the beginning of coding. As we proceed through the example, we define and explain the various types of design diagrams created.

The gas station in this example allows customers to purchase gas (self-service), to pay for maintenance work done on their cars and to lease parking spots. Some local businesses have billing accounts set up to receive a monthly bill, instead of paying at the time of purchase. There is always a cashier on-duty at the gas station to accept cash payments or perform system maintenance, as necessary.

The requirements we are concerned with for the purposes of the example are *excerpts* from the requirements document describing the Gas Station Control System (GSCS), and describe how the system receives payment from the customer. A customer has the option to be billed at the time of purchase, or to be sent a monthly bill and pay at that time. Customers can always pay via cash or credit card. Table 4.1 describes some concepts about this part of the problem.

Concept	Description
Credit card reader	The credit card reader is a separate piece of hardware mounted at each gas pump. The internal operations of the credit card reader, and the communications between the GSCS and the card reader, are outside the scope of this document. When the customer swipes his or her credit card through the card reader, the card reader reads the credit card number and sends it to the GSCS. If the credit card number cannot be read correctly, an invalid token is sent to the GSCS instead.
Credit card system	The credit card system is a separate system, maintained by a credit card company. The internal operations of the credit card system, and the communications between the GSCS and the credit card system, are outside the scope of this document. The GSCS sends a credit card number and purchase amount to the credit card system in order to charge a customer's account; the credit card company later reimburses the gas station for the purchase amount.
Gas Pump	The customer uses the gas pump to purchase gas from the gas station. The internal operations of the gas pump, and the communications between the gas pump and the GSCS, are outside the scope of this document. The gas pump is responsible for recognizing when the customer has finished dispensing gas, and for communicating the amount of gas and dollar amount of the purchase to the GSCS at this time.
Gas Pump Interface	The gas pump interface is a separate piece of hardware mounted at each gas pump. The internal operations of the gas pump interface, and the communications between the gas pump interface and the GSCS, are outside the scope of this document. The gas pump interface receives a message from the GSCS and displays it for use by the customer. The gas pump interface also allows the customer to choose from a number of options, and communicates the option chosen to the GSCS.
Cashier's interface	The cashier's interface is a separate piece of hardware mounted at the cashier's station. The internal operations of the cashier's interface, and the communications between the cashier's interface and the GSCS, are outside the scope of this document. The cashier's interface is capable of displaying information received from the GSCS. The cashier's interface is also able to accept input from the cashier, including numeric data, and communicate it to the GSCS.
Customer	The customer is the client of the Gas Station. Only registered customer can pay bills monthly. Name, address, telephone number and account number are the features that will describe a registered customer.

Table 4.1 - Glossary

The functional requirements that were defined for the billing part of the gas station system are as follows. As in any other system development, the initial set of requirements obtained from discussion with the customer may contain some errors that could potentially impact system quality.

1. After the purchase of gasoline, the gas pump reports the number of gallons purchased to the GSCS. The GSCS updates the remaining inventory.
2. After the purchase of gasoline, the gas pump reports the dollar amount of the purchase to the GSCS. The maximum value of a purchase is $999.99. The GSCS then causes the gas pump interface to query the customer as to payment type.

2.1. The customer may choose to be billed at the time of purchase, or to be sent a monthly bill. If billing is to be done at time of purchase, the gas pump interface queries the customer as to whether payment will be made by cash or credit card. If the purchase is to be placed on a monthly bill, the gas pump interface instructs the customer to see the cashier. If an invalid or no response is received, the GSCS bills at the time of purchase.

3. If the customer has selected to pay at the time of purchase, he or she can choose to pay by cash or credit card. If the customer selects cash, the gas pump interface instructs the customer to see the cashier. If the customer selects credit card, the gas pump interface instructs the customer to swipe his or her credit card through the credit card reader. If an invalid or no selection is made, the GSCS will default to credit card payment.
4. If payment is to be made by credit card, then the card reader sends the credit card number to the GSCS. If the GSCS receives an invalid card number, than a message is sent to the gas pump

interface asking the customer to swipe the card through the card reader again. After the account number is obtained, the account number and purchase price are sent to the credit card system, and the GSCS and gas pump interface are reset to their initial state. The purchase price sent can be up to $10000.

5. The cashier is responsible for accepting the customer's payment and making change, if necessary. When payment is complete, the cashier indicates this on the cashier's interface. The GSCS and the gas pump interface then return to the initial state.
6. If payment is to be made by monthly bill, the purchase price is displayed on the cashier's interface. The cashier selects an option from the cashier's interface, alerting the GSCS that the payment will be placed on a monthly bill. The GSCS then prompts the cashier to enter the billing account number.

6.1. The customer must give the billing account number to the cashier, who then enters it at the cashier's interface. If a valid billing account number is entered, then the billing account number, purchase price, and a brief description of the type of transaction is logged. If an invalid billing account number is entered, an error message is displayed and the cashier is prompted to enter it again. The cashier must also have the option to cancel the operation, in which case the cashier's interface reverts to showing the purchase price and the cashier can again either receive cash or indicate that monthly billing should be used.

7. To pay a monthly bill, the customer must send the payment along with the billing account number. The cashier enters monthly payments by first selecting the appropriate option from the cashier's interface. The GSCS then sends a message to the cashier's interface prompting the cashier to enter the billing account number, the amount remitted, and the type of payment. If any of these pieces of information are not entered or are invalid, payment cannot be processed; an error message will be displayed, and the cashier's interface will be returned to the previous screen. If the type of payment is credit card, the credit card account number must also be entered, and then the paper credit card receipt will be photocopied and stored with the rest of the year's receipts.
8. Unless otherwise specified, if the GSCS receives invalid input it will send an error message to the cashier's interface. The cashier will be expected to take appropriate action, which may involve shutting the system down for maintenance.

Performance and extensibility, two non-functional requirements (Chung et al., 1999) that can influence decisions regarding low level design were also used:

1. The system must always respond to customer input within 5 minutes.
2. The system should be easy to extend, so that if necessary another payment option (e.g. bankcard) can be added with minimal effort.

4.1 Requirements Activities

The problem description and requirements were generated first. Then, the requirements were inspected to ensure they were of high enough quality to support high-level design and fully represented the functionality needed to build the system. This requirements inspection was done using PBR. For this system we used the customer and tester perspectives because during the inspection we were able to identify defects while producing artifacts capturing the system's functionalities (use cases) and information (test cases) that might be used later for application

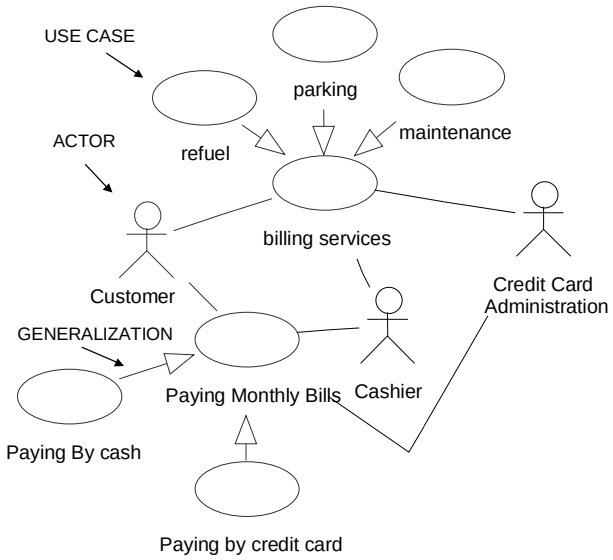
testing. The use cases in particular were felt to be a useful representation of the system functionality and worth the time required for their creation, since they provide a very understandable format for communication between system designers and the customers. Moreover, use cases feed into later stages of the lifecycle by helping identify objects, develop testing plans, and develop documentation. So, this representation was expected to provide additional benefits for developers as well as to be useful for validating whether the system met the customer's expectations.

Applying PBR to the gas station requirements resulted in the identification of some defects. The two perspectives helped the readers find different kinds of defects. First, by using the tester perspective, an omission was found in the requirement 5. Domain knowledge indicated that the cashier needs to know the purchase price if he/she is to handle the cash transaction. The tester perspective allowed the reader to see that because all inputs have not been specified, the requirement cannot be tested. Also using the tester perspective, a defect of extraneous information was found in requirement 7. The requirement states that receipts are copied and stored. However, such activity is clearly outside the scope of the system. It can not be tested for during system test.

Using the customer perspective, an incorrect fact was identified in requirement 3. By using domain knowledge the customer recognized that defaulting to credit card payment is an incorrect response. Because this functionality should not have been implemented the way it was described, the defect was categorized as an incorrect fact. Also, the customer perspective helped uncover that requirement 6.1 has an ambiguous description that could result in a number of different implementations. "A brief description of the type of transaction" seems like a reasonable requirement, but exactly what information is stored? What does "transaction type" mean? Purchase of gas/maintenance? Paid in full/partial payment? Paid by credit card/cash/monthly bill?

The use cases produced by PBR were the first UML design artifact produced for this project. Figure 4.1 shows a use case diagram highlighting its components and corresponding description. (There is a wide variation among organizations and even projects as to how formally use cases are specified. In the example system, an English description was used for the system functionality.) The use-case diagrams model the system's functionalities by showing descriptive scenarios of how external participants interact with the system, both identifying the events that

occur and describing the system responses for these events. Use case diagrams can also represent relationships (association, extend, generalization and include) among use cases or between actors and use cases. An *association* is the relationship between an actor and a use case. In the figure an example is the line between "Customer" and "billing services". An *extend* relationship shows that one use case is being augmented by the behaviors of other use case. In the figure an example of this the relationship between "parking" and "billing services." The *generalization* shows that one use case is a specialization of another one, e.g. "Paying Monthly Bills" in relation to "Paying by Cash" while the *include* relationship shows that an instance of one specific use case will also include the sequence of events specified by another use case.



Specific use case for "Paying Monthly Bills":
Customer sends payment and account number to the cashier that selects the payment option and must inform account number amount remitted and type of payment. If any of these information are not entered, payment can not be completed (cashier interface will display a message) and the operation will be cancelled.
Types of payments:
1) by cash
Cashier informs account number and amount been paid
2) by credit card
Cashier informs credit card, amount and account number
Gas Station ask Credit Card System to authorize payment
if authorization is ok payment is made
if payment is not authorized or failed Cashier receives a message describing that payment was not able to be processed. Cashier must repeat operation once more before cancel all the operation

Figure 4.1 - A use case diagram and the specific description for one of the use cases identified.

PBR uses the equivalence partitioning technique (Jalote, 1997) to read and produce test cases. Test cases help identify defects and provide a starting point for real test cases of the system (so developers don't have to start from scratch at that phase.)

For example, the following test cases were produced for requirement 2:

Requirement Number:	**2**
Description of Input:	**dollar amount of purchase**
Valid Equiv. sets:	**Valid dollar amts.**
Test cases:	**$100** **$13.95**
Test result:	**Instruct gas pump interface** **to query for payment type**
Invalid Equiv. sets:	**Negative dollar amts.** **dollar amts. > $999.99**
Test cases:	**-$5.00** **$1000.00**
Test result:	**display error at cashier interface**

The same approach was used to build the test cases for each requirement and identify defects. When readers finished the requirement inspections, the potential defects were evaluated and fixed in the requirements. At this point, there is a choice as to whether the requirements should be re-inspected, depending on the number of defects and problems that were found. For this system, one inspection was deemed to be sufficient. At the end of this phase, a set of fixed requirements, corresponding test cases and use cases, was available to continue the design process.

4.2 High Level Design Activities

At this point, all the concepts specified by the requirements have been reviewed and a high level representation for the functionalities was identified and modeled by the use case diagrams. The next step was to organize those concepts and functionalities using a different paradigm. From this point until the end of integration testing, all the activities were driven by the object-oriented paradigm. The main issue was: how problem features (concepts and functionalities) could be classified and organized to allow developers to design an object oriented solution for the problem.

The use cases and requirements descriptions are the basis for the high-level design activities (see figure 3.2). They represent the domain knowledge necessary to describe the features and make them understandable to the development team. The static and dynamic properties of the system need to be modeled. Moreover, use cases and requirements descriptions

are used in design inspection because they represent the truth about the problem, and allow the solution space to be limited for the developers.

As we stated in Section 3, UML artifacts can be built in any order. Developers can tailor a development process to fit their needs. In our example development process, a draft class diagram was produced first in order to explore the organization of the domain concepts. Class Descriptions were produced and enhanced through all the design activities, regardless of the type of artifact being built. Therefore, a first draft for the class description was also produced. Subsequent activities refined the class diagram and described the functionalities that had to be part of the solution. Doing so, developers explored a design perspective focused on the domain concepts rather than just the functionalities of the system. We have observed that the use of such approach drives designers to model essential domain elements, independent from the solution, and being more suitable for future reuse.

This initial picture of the basic elements of the problem gave designers the ability to model the functionalities and understand how external events impact the life cycle of the objects and system. It was also possible to identify the different chunks of the problem, allowing the identification of different classes packages. Classes were grouped into packages by their structure or type of services they offered. By doing so, developers got some information that was used to improve the definition of the application architecture, for instance, grouping all classes that contain interfaces for external systems into one package.

Next, the dynamic behavior of the system was modeled by creating the sequence and state diagrams. Using this information, the Class Diagram was then refined. All along the way, the Class Descriptions were updated to be consistent with the information in the other diagrams. Finally the Package and Activity diagrams were created. Each of these will be explained in more detail below.

Once UML design artifacts are built, developers can apply inspections to verify their consistency and then validate them against the requirements and use cases used to define the problem. Object-Oriented Reading Techniques (OORTs) were used to support inspections of UML high level design artifacts in the context of this design process.

After finding and fixing high-level design defects, which sometimes can imply some modifications in the requirements and use cases, developers had a complete set of quality design artifacts representing the framework to be used for continuing design. The next steps included

dealing with low level issues, such as decisions regarding support classes, persistence and user interface and also restrictions imposed by the implementation environment. The models produced guided coding and testing activities.

The following sections describe this process step by step, showing the artifacts that were produced and how inspections were applied to ensure quality and reduce the number of design defects.

4.2.1 Step 1: Class Diagrams and Class Descriptions

Using the repaired requirements descriptions and use cases, the designers needed to identify and extract the different domain features that would compose the design model. At this point, there is always a choice of approaches for how to proceed. One option for developers is to apply an organized and systematic technique to capture such features. A first draft of the models is produced using linguistics instruments to identify the semantics and syntactic involved in such documents (Juristo et al., 2000). Another option is to use a more relaxed approach, where some linguistics issues are considered but without the level of detail or formalization (Rumbaugh et al., 1992). In this example, designers used the Rumbaugh approach to look for nouns, verbs and adjectives used in the requirements and use cases to get a first idea about the classes, attributes and specific actions.

Identifying the nouns gave designers initial candidates for the system classes. The class diagram was then created to model this initial class structure. This diagram captures the vocabulary of the problem. It defines the concepts from the domain that must be part of the solution and shows how they are related. The expected result is a model of the system information with all the features (attributes and behaviors) anchored to the right classes. These features delimit the objects' interface, acting like a contract for the class (Meyer, 1997). By identifying the actions for each object type and the visibility of those objects, the class diagram clearly defines how objects can communicate.

Figure 4.2 shows an example of the initial class diagram for the Gas Station control system[7]. Identifications of the basic diagram elements were inserted to show some of the different type of information that can be modeled, such as classes, aggregations, associations and simple inheritance. Classes (representing the object types) and their static relationships are the

[7] The complete set of artifacts for this system, including requirements descriptions, can be found in http://www.cs.umd.edu/projects/SoftEng/ESEG

basic information represented by class diagrams. A class representation has a name, encapsulated attributes and behaviors, together with their restrictions (constraints). The main static relationships for classes are subtype (e.g. Gas *is a* Product) and associations, which can be expanded to acquaintances (e.g. a Registered Customer *makes* a Purchase), aggregation (Inventory *consists of* Products) and composition (e.g. a Purchase *is part of* a Bill).

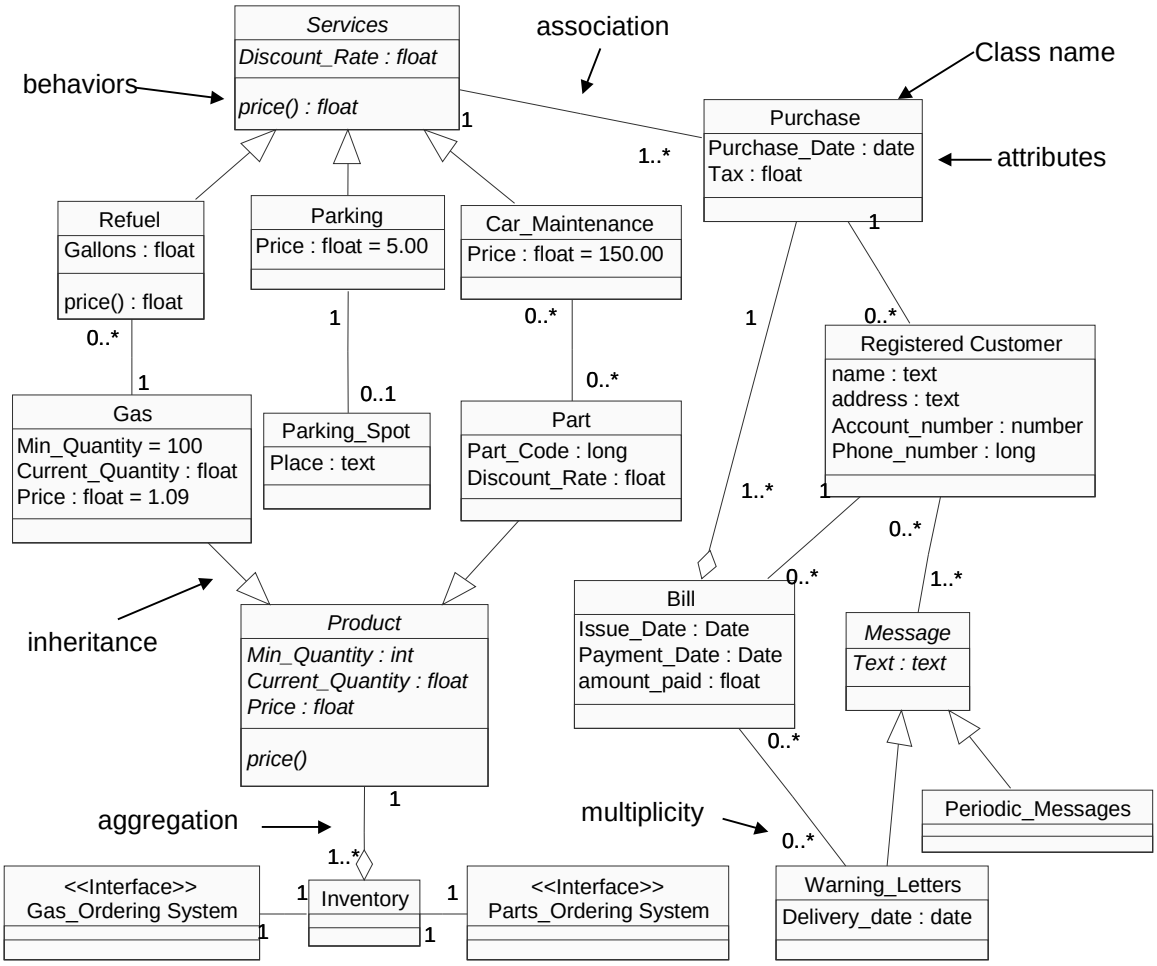


Figure 4.2 - An example of an UML Class Diagram

Subclasses (subtypes) are modeled by specialization. An inheritance mechanism asserts that a subclass inherits all the features from the superclass. This means that all the attributes (data structures), behaviors (services) and relationships described in one class (superclass) are immediately available for its subclasses. Single (one superclass) and multiple (more than one superclass) inheritances are both possible. In the example, because the class “Parking” is a subclass of “Services”, it contains the attribute “Discount_Rate” and it also receives the ability to

communication with the "Purchases" class. Abstract classes are used to improve the model by clarifying the classification and organization of the classes. However, abstract classes can not be instantiated.

Associations represent the relationships among instances of a class (e.g. a Registered Customer *makes* a Purchase), but conceptually are shown as relationships among classes. Roles and the number of objects that take part in the relationship (association multiplicity) can be assigned for each side of the relationship. A Registered Customer can make 0 or more purchases, but each purchase can be made by only one customer. Relationships can also be used to represent the navigability perspectives (e.g. to give an idea about which object is the client) and specify the visibility to the objects.

At this point in the design process, designers realized that the reasons behind their decision to create a Registered Customer class may be lost if more information about this class and its attributes was not captured. As a result, the Class Description was created and more information was inserted. This included the meaning of the class as well as behavior specifications and details about relationships and multiplicity. This could also include the constraints and restriction formalization using the Object Constraint language (OCL), specification of interfaces and communications such as defined by the CORBA standard and also the UML models mapping to XML provided by the XMI specifications (OMG, 1999).

Class name: Registered Customer
Documentation: The customer is the client of the Gas Station. Only registered customer can pay bills monthly.
External Documents defining the class: Glossary
Cardinality: n
Superclasses: none
Interface:
Attributes:
Name: *text* : It represents the name of a customer. First + last name is the normal way that a name is represented
address : *text* : This is the mail address for the customer. An address should be described using the following format: 1999 The Road Ave. apt. 101
Gas Station City - State – Zip Code
account_number : *long*: Customer account number is the numeric identification of the customer in the context of the Gas Station control System
phone_number : *long* : a phone number to the customer: (area code)-prefix-number
Operations: none

Figure 4.3 - An example of a class description

Figure 4.3 shows the class description example generated for the Registered Customer class. Words in bold represent the template fields used on this project. Words in *italic* are types for the attributes. There is one description like this for each class in the class diagram.

The class description artifact complements the information described by the other diagrams. It holds detailed descriptions for classes, attributes, behaviors, associations and consequently all other important characteristics that need to be described but cannot be done by other diagrams. It acts as a data dictionary and it is not formally defined by the UML standard, because it is an implicit document produced during design. Because there is no standard template for this artifact, one can be derived directly from the diagrams to ensure consistency. The Class description evolves throughout the design process and at the end must hold all the information necessary to begin low level design.

4.2.2 Step 2: Interaction and State Diagrams

At this point, developers already had a better view about the problem. They modeled the use cases and produced a first class diagram. The Class Diagram does not show how the behaviors can be put together to accomplish the functionality. Most behaviors are the basic functions for the classes. So, designers needed to understand the functionalities that are required and how to combine the behaviors to accomplish them. The relationships on the Class Diagram specify only which objects are related to one another, not the specific behavior or message exchanged between them. To continue development, it was necessary to show how information should flow among the objects, represented by the sequence of messages and the data they carry.

- The use cases contained the information the developers needed to describe system functionality. However, they described functionalities and events using an informal notation. They do not clearly represent how objects interact and which messages are exchanged, but merely describe the different scenarios.

Aside from functionality, conditions and constraints are also described by use cases, and more explicitly, by the requirements descriptions. A condition describes what must be true for the functionality to be executed. A constraint must always be true regardless of the system functionality.

Interaction diagrams met the needs of developers at this point because they represent system functionalities more formally. These diagrams model the use case scenarios including their conditions and constraints. Basically, interaction diagrams provide a way of showing which

messages are exchanged between objects to accomplish the services and functionalities of the system. Typically, each use case has one associated interaction diagram. However, for complex use cases more than one interaction diagram can exist, breaking down the use case complexity while capturing the messages and services necessary to represent the whole functionality.

There are two forms of interaction diagrams: sequence and collaboration. Sequence diagrams show the flow of messages between objects arranged in chronological order. Normally, an actor or an event initiates a messages sequence. Some designers suggest that sequence diagrams are the best form of interaction diagrams to be used when modeling real-time specifications or complex scenarios (OMG, 1999).

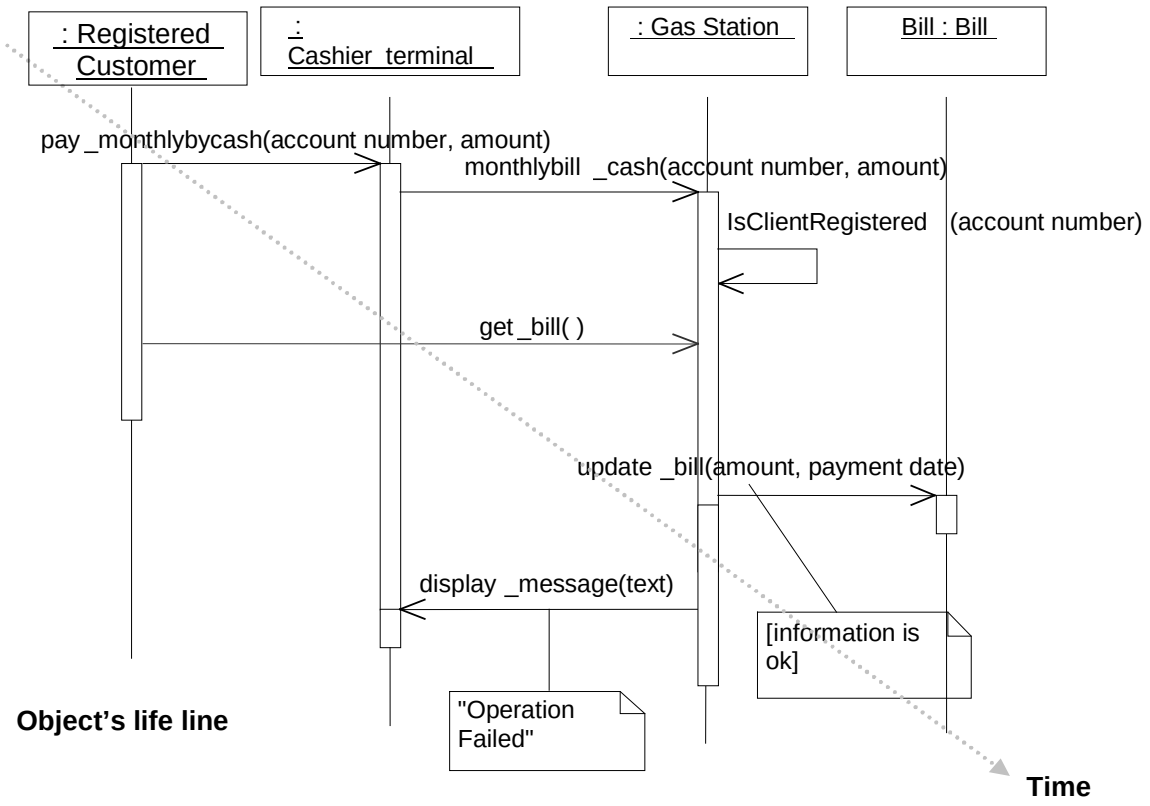


Figure 4.4 - An example of a sequence diagram

Figure 4.4 shows an example of a sequence diagram for the scenario (pay by cash) represented in Figure 4.1. Object lifelines, a box at the top of a dashed vertical line, represent objects. An object lifeline holds all interactions over time in which the object participates to achieve a particular functionality. An object that shows up in different sequence diagrams has different lifelines, one for each sequence diagram. For example "Bill" could show up in this

sequence diagram as well as “Paying by Credit Card.” An arrow between object lifelines is a message, or *stimuli*, (labeled with at least a name). For example “get_bill()”, where the origin is “Registered Customer” and the receiver is “Gas Station”. Each message is usually associated with one behavior encapsulated by the receiving object's class. Additional modeling situaions that can be captured include: Self-delegation (an object sends a message to itself such as IsClientRegistered(account number)), condition (to indicate conditions that must be observed to send or receive a specific message, such as [information is ok]), and iteration marker (that indicates a message can be sent several times to multiple receiver objects). The order of messages in the sequence is represented by their position on the object lifeline, beginning at the top.

Collaboration diagrams are a combination of sequence diagrams with object diagrams and display the flow of events (usually associated with messages) between objects. They show the relationships among the objects and the different roles that objects play in the relationships. Figure 4.5 displays the collaboration diagram for the sequence diagram of Figure 4.4. Objects, in this case, are represented as a box, for example “Gas Station”. The arrows indicate the messages (events) sent within the given use case, for example “display_message(text).” Message order is shown by numbers instead of by position as used in sequence diagrams. So, “1:pay_monthlybycash” is followed by “2:monthlybill_cash”, and so on.

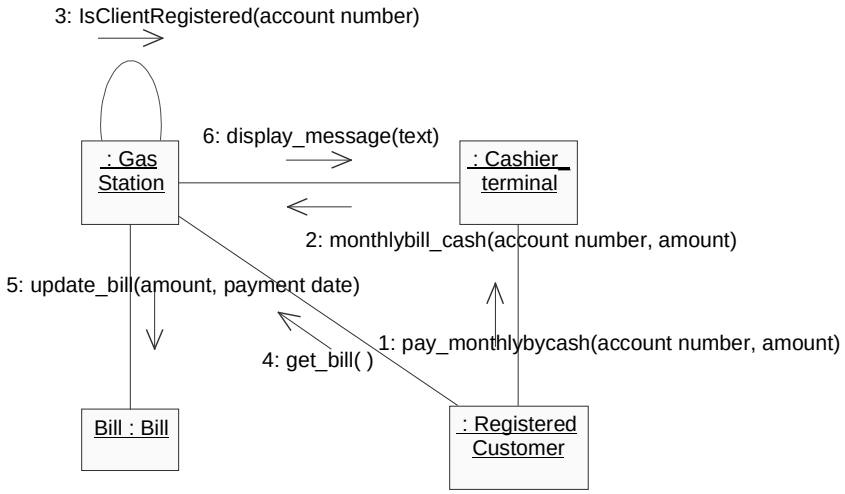


Figure 4.5 - A Collaboration Diagram

Interaction diagrams are adequate for capturing the collaboration among objects. Regardless of the form used, designers can see which objects and messages are used to capture

the functionalities of the system. However, functionalities are represented in an isolated manner. By this we mean that this describes each scenario without considering the other ones. But, some systems are heavily affected by external events. For these systems, some classes have very dynamic instances. This dynamism occurs because of the changing states of the objects due to external events. The designers of this system decided that this system fell into this class. Because of this the designers found it difficult to understand each specific class by itself.

Because the object states can impose constraints on the use of the object, they can affect the functionality of the system. In these cases, modeling of the different situations that change the state of the object is worthwhile. This model helps identify the events and the actions that cause state changes. It supports the comprehension of an object's life cycle and specification of the constraints that will drive objects to be in a consistent state.

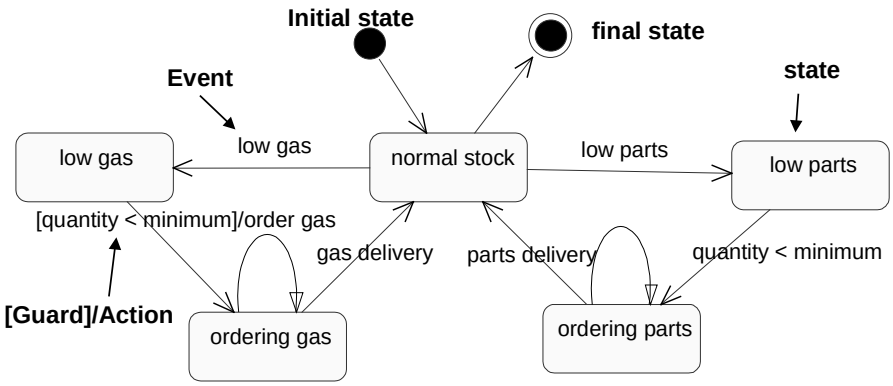


Figure 4.6 - A Statechart

The designers decided that this was necessary information for this system. So, they created the UML diagram that captures the states of an object and its events, called a statechart (Harel and Naamad, 1996). Figure 4.6 shows a statechart for the Inventory class. This diagram describes the basic state information about the states themselves (the cumulative results of the object behavior, or the collection of attributes value for a specific instance, for instance "ordering gas" and " ordering parts") and transitions (a system event, or external occurrence that induces a system or object state change, for instance "gas delivery" or "parts delivery"). Actions can also be associated with states. Doing so, designers can specify which action is triggered when the object reaches a specific state, keeps the current state or leaves the current state. For example, when the state "low gas" is reached the action of "order gas" should be triggered. Constraints

(guards) are normally associated with transitions, showing when objects can change from one state to another. In this case, when the quantity is less than some minimum value, the “low gas” state is entered. Additionally, nesting can break down inherently complex states when necessary.

It is common to find projects that do not make use of state diagrams. However, when these diagrams are used, their combination with interaction diagrams represent a way to identify testing scenarios and prepare complimentary test cases for the system (Vieira and Travassos, 1998), (Offutt and Abdurazik, 1999).

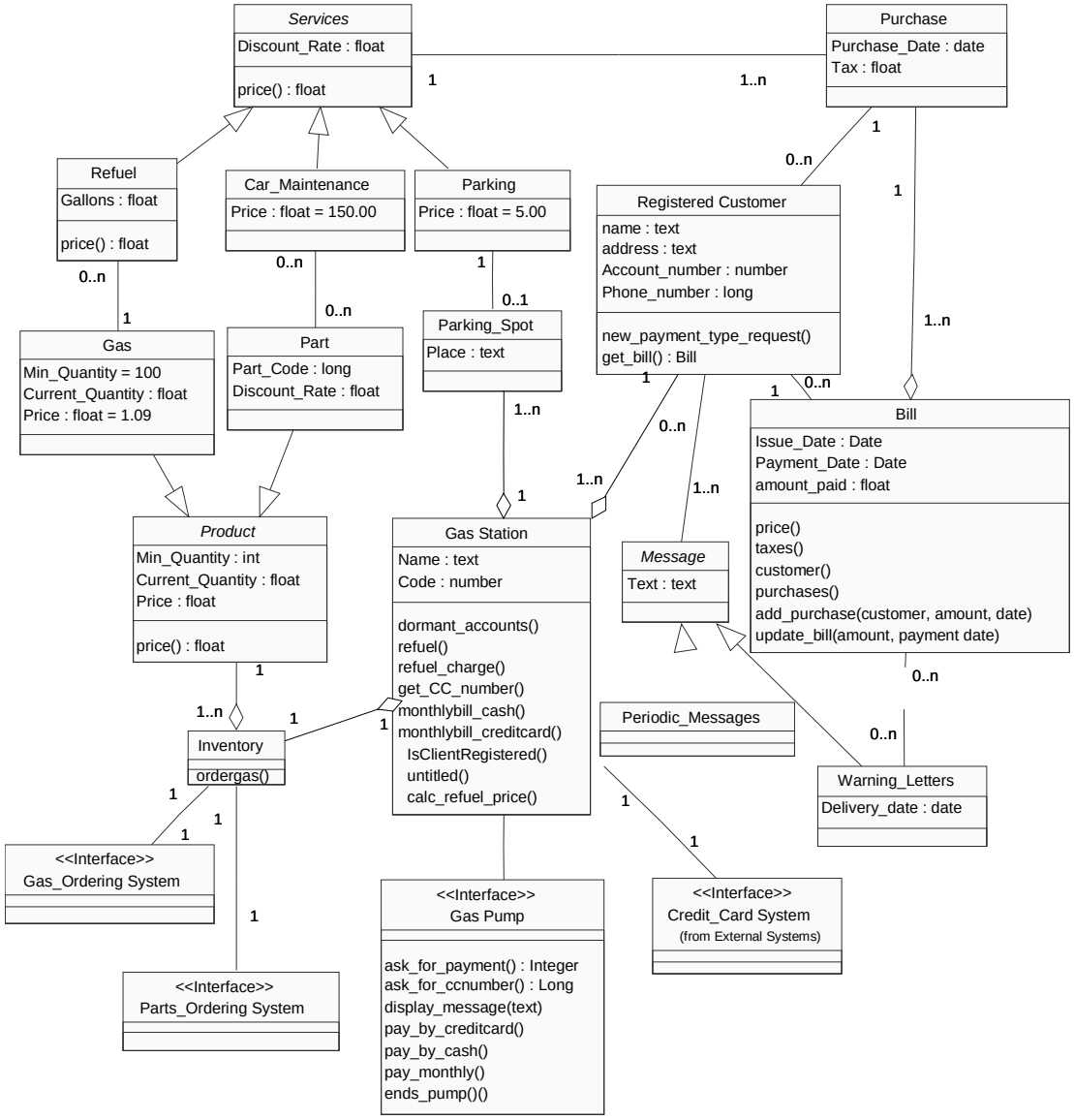


Figure 4.7 - A Refined Class Diagram for Gas Station Control System

4.2.3 Step 3: Refining Class Diagrams

At this point, designers have a first draft for most of the diagrams and specifications for the functionalities. However, the models are not completely defined and specified since typically additional services or messages will need to be used to model the dynamic view. This is normal and represents how designers are organizing the design, finding new features, grouping behaviors, or even identifying new services that are necessary or make sense when the objects are combined to extract the required functionalities. New classes can show up during dynamic modeling to hold new services. The messages that are used by the objects and the information they carry can be identified. The object's interface to the external world is defined and must be represented in the class diagram and fully specified in the class description.

For the gas station example, some results from this step can be seen in Figure 4.7. New classes were inserted based on services used to represent required functionalities (e.g. Gas Station). Attributes types and methods signatures were identified (e.g. Bill features). Moreover, some actors needed to be represented as classes (e.g. interfaces to the external actor) to allow for the communication between the system's objects and external participants (e.g. Gas Pump and Credit Card interfaces). As expected, new information was described in the class description, to better specify the new behaviors, attributes and other features.

After dynamic modeling of the GSCS, designers decided to prepare a first set of product measures. Having updated the class diagram, the classes were expected to be more stable at this point, with most of the functionality described. These measures were expected to be useful during low level design as a way to identify complex classes or class hierarchies, and thus to provide some guidance about which part of the design structure must be modified to reduce structural design complexity (Henderson-Sellers, 1996)(Travassos and Andrade, 1999) or to identify the classes that are more fault prone (Basili et al., 1995). Section 3.3.1 described some metrics that can be used to measure the product. The values determined for the metrics **WMC**, **DIT**, **NOC** and **CBO** for some classes of the GSCS (recall Figure 4.7) are shown in Table 4.3.

Having all these artifacts, developers now had completed a broad view of the problem. Although it was not possible to guarantee that the design was complete, decisions about packaging and internal structuring could take place. But, before that, object-oriented reading techniques were applied to identify possible defects in the design and ensure that such decisions were made on a sound basis.

As discussed in Section 3.2.2, Object-Oriented Reading Techniques (OORTs) are a set of reading techniques that have been tailored for defect detection in high-level object-oriented design documents. Horizontal reading ensures that all the design artifacts represent the same system and tends to find more defects of inconsistency and ambiguity. For instance, when the diagrams from Figures 4.4 and 4.7 were inspected, at least 3 possible defects (discrepancies) were found using a horizontal reading technique (class diagram against sequence diagrams):

1) gas station class has no representation for the message get_bill();
2) there is no Cashier_terminal class described in the class diagram;
3) gas station sends a message to an object that seems to not exist.

Class Name	WMC	DIT	NOC	CBO
Services	1	0	3	1
Refuel	1	1	0	2
Car_Maintenance	1	1	0	2
Product	1	0	2	1
Gas	1	1	0	2
Part	1	1	0	2
Registered Customer	2	0	0	4
Gas Station	9	0	0	5

Table 4.3 GSCS Metrics and values

The first discrepancy is an inconsistency. If gas station object receives the get_bill() message, it means that its class must have a description for such a message. Developers could not be sure whether or not the message get_bill() was appropriate and necessary in the context of the system, but the OORT did raise the question by highlighting the discrepancy between the diagrams. Discrepancies 2 and 3 are potential defects, but it was not possible to know if they were real defects just by using the information in the design artifacts. Designers reviewed the discrepancy list as a team to discuss which ones were real defects and needed to be fixed prior to vertical reading. Discrepancies that were not seen as real defects were good candidates for further evaluation by vertical reading after the high level design was completed.

4.2.4 Step 4: Package and Activities diagrams

The development of complex systems demands significant management efforts. The identification of the parts of the system that will be implemented and their distribution among the development team is one of the important management tasks. UML provides a diagram, the package diagram, that can be used to represent the high level grouping of classes. Designers can

group classes by different characteristics such as structure, hierarchy or even functionality. These diagrams are used to represent how designers broke down a large and complex system into smaller units, clustering the classes in well-defined parts, called packages. To guarantee that the information about the dependencies between classes is not lost, package diagrams allow for the representation of such a dependencies between the packages. For the GSCS system, after dynamic modeling and the associated changes to the class diagram, the system was felt to be of sufficient complexity for package diagrams to be useful. Figure 4.8 shows the package diagram created for the system.

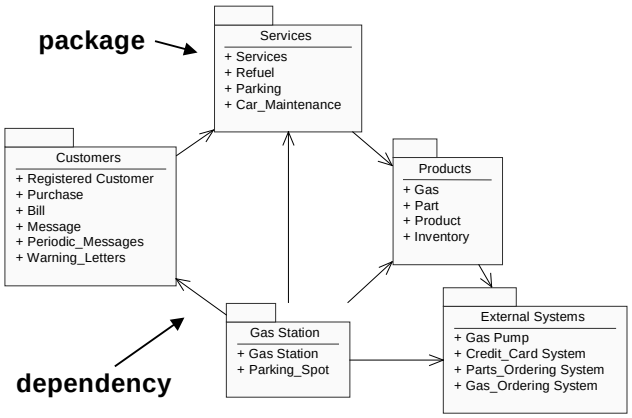


Figure 4.8 – An example of a Package Diagram

Usually, a dependency between two classes exists if changes to the definition of one class may cause changes to the other one. In this case, dependencies can be listed as 1) a class (object) sends a message to another class; 2) a class has another class as part of its data, and 3) a class mentions another one as a parameter to one of its behaviors. When any two classes from different packages have dependencies between them, the packages that hold them also have a dependency. For large projects this is vital information because developers can use it to identify which packages must be integrated or will be impacted when modifications are introduced. Developers can control the level of granularity at which they are grouping and defining packages, for instance, by nesting packages within other packages.

Dependencies between packages support design decisions. For example, based on dependency information developers can identify which packages and parts of the static design must be rearranged to reduce system coupling. Also, by identifying the classes that can be grouped, developers can produce useful information for testing activities, for example to bind a

set of system concepts that may be tested together. Information regarding package contents and visibility may be shown by the diagram.

Activity diagrams can be more useful for certain types of systems, mainly those that involve multiple threads, and need to detail which internal events will happen after the system receives an external event from an actor. Different from state diagrams, activity diagrams represent the services that must be accomplished when internal events happen. They can be used to model activity flow of services (functionality). Despite this difference, activity diagrams have some similarities to statecharts. Activities are similar to states while events are similar to transitions. They are useful to represent functionalities that involve more than one class and set of services. Activity diagrams are useful when modeling business processes. An example of this diagram with some of its elements can be found in Figure 4.9.

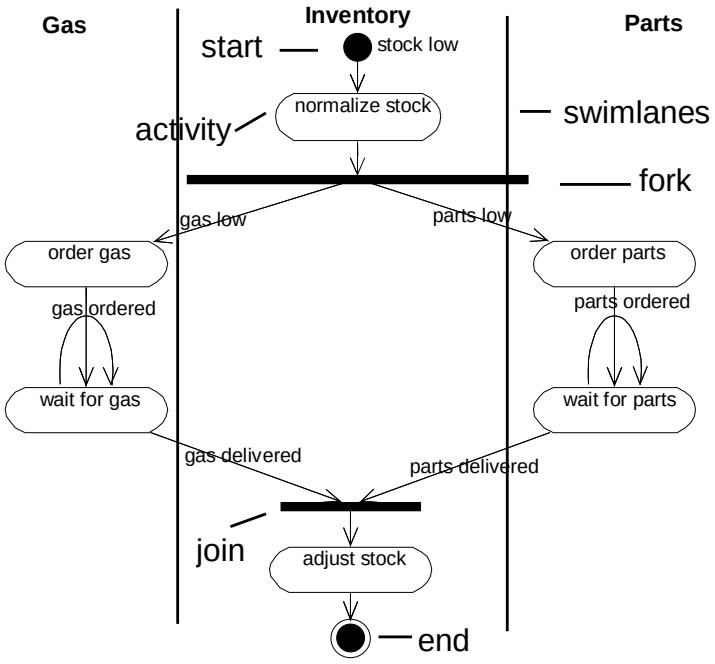


Figure 4.9 – An Activity diagram

At this point, all the UML high level design artifacts had been produced. Horizontal reading was applied and the discrepancies identified as defects were solved and fixed. However, some of the reported discrepancies were still unresolved. Vertical reading was then applied to ensure that design artifacts represented the same system described by the requirements and use-cases. Because documents from different life cycle phases, using different levels of abstraction and detail, were compared, vertical reading found more defects of omission and incorrect fact.

For example, horizontal reading had determined that the sequence diagram from figure 4.4 was consistent with all the other high-level design artifacts. Applying a vertical reading technique (sequence diagrams against use cases) it was read against the use case represented in Figure 4.1. This sequence diagram intends to capture the use case "pay by cash", which is a specialization of "pay monthly bills" use case. Although representing the same functionality, the reading technique was needed to compare the diagrams due to the different levels of abstraction used. Use cases normally describe the scenarios using high abstraction. Readers need to explore these differences when inspecting the documents.

Two different scenarios can be seen in the context of the use case. For instance, the use case scenario "Customer sends payment" was captured by the message pay_monthlybycash(account number, amount). The sequence of messages monthlybill_cash, IsClient registered, update_bill and display_message captured the scenario "Cashier verifies information and receive payment". However, the message get_bill() did not seem to be part of the use case (a customer already has the bill before paying it) and should not be part of the sequence diagram. This message had been marked as a discrepancy when horizontal reading was applied. The use of the vertical reading techniques identified that it was a real defect that must be fixed before low level design.

After all the high-level UML design artifacts were inspected and the defects fixed, a stable description for the problem was ready. These models were important during low level design, the next design activity.

4.3 Low Level Design Activities

As stated earlier, one of the benefits of UML is that designers use the same set of constructs to represent the different aspects of the system, making the transition from requirements to high-level design to low-level design a smooth process. The results from the high level design compose the problem domain design. They must be modified and extended to include all technical restrictions imposed by the different resources (e.g. development environments, programming languages, computer architectures and so on) that will be used to build the software and by the non-functional requirements, such as performance, usability and maintainability. One necessary modification may be caused by the reuse of early projects and coded classes, which impose the reorganization of the current classes and relationships. Another

could be the level of inheritance that must be observed now due to characteristics available in the programming language. Low level issues, such as the definition of low abstraction classes or even the detailed description for an algorithm, are important for this design phase.

The types of diagrams produced in low level design are basically the same ones that were produced for high level design. The main difference is the level of detail. Moreover, new classes will show up to deal with persistence, management and user interface issues. Methods will have their signatures fully described and the models will be prepared in such way that programmers can use them as the basis for coding and testing activities, including the specification of the components and the different devices that will compose the final solution.

Different software components support the description of the solution for a problem. Each component normally represents a physical module of code. Although a package can hold more than one component, components can be viewed as a low-level package representation. Sometimes, a class that belongs to a specific package can be present or used in different components depending on the type of functionality the developer is representing.

A component diagram shows the components implemented in the system, together with their communication lines (dependencies). Dependencies highlight the coupling among components and specify which interface for the component is being used. This diagram is normally produced when designers have a clear definition about the solution and have already defined the architecture for the software.

The information captured by components diagrams support the identification of system integration interdependencies. This specific type of information will be useful when planning testing and defining delivery and maintenance priorities. Figure 4.10 shows an example of a component diagram.

Component diagrams represent system organization from the software perspective. For some system types (e.g. web-based applications, distributed applications) the physical relationship between software and hardware plays an important role in describing how the system will be distributed and organized for deployment. UML provides deployment diagrams to describe this type of information.

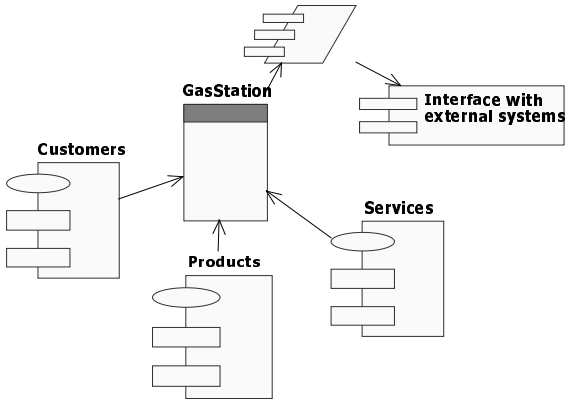


Figure 4.10 - An example of a component Diagram

By representing the different pieces of hardware (nodes, such as devices, sensors, computers and so on), and the communication paths (connections) between nodes, deployment diagrams help to clarify the existing integration features, allowing for the identification of possible communication bottlenecks or that demand specific infrastructure for testing and evaluation.

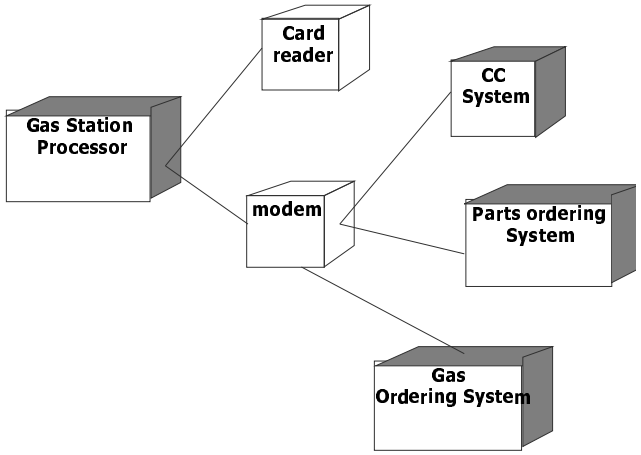


Figure 4.11 - A deployment diagram

Some designers suggest combining components with deployment diagrams, showing the components inside the corresponding nodes. Doing so, they get the benefits of both representations using just one diagram. Figure 4.11 shows a deployment diagram in its standard form.

There is much written describing low level design activities. To produce a complete list here is not feasible. However, the reader who is motivated by these discussions can find some of

the following works useful: a classical text about OO design and the use of design patterns to describe software solutions can be found in (Gamma et al., 1995). It describes useful design concepts and suggests patterns for the different design situations. The discussions are focused on the structural organization of the models. Although it does not use UML as the modeling language (the authors used OMT, one of the UML roots), their descriptions are clear enough to allow the immediate mapping to UML. A complimentary text can be found in (Buschmann et al., 1996). (Meyer, 1997) has an in depth discussion about basic types and objects exploring different issues such as management and persistence. (Henderson-Sellers, 1996) raises some useful discussions about design complexity and suggests some ways to use metrics to identify high structural complexity design parts.

5. Maintenance or Evolution

The process model shown in Figure 3.1 has a definite end point for the development process (delivery to the customer). This is a useful abstraction, but currently in industry very few systems are built in their entirety and then shipped to the customer. Most software development involves some type of incremental development, or enhancement-type maintenance. Incremental development can be defined as a process whereby the system is broken into smaller pieces and the goal of each release is to add a new piece to the software. For more information on incremental development see (Pressman, 1997), (Pfleeger, 1998). In these development or maintenance cases, software development takes place in the presence of some set of *reusable assets*.

We use the term *reusable assets* to refer to the set of artifacts in existence from any operational system that needs to be expanded, improved, updated or otherwise modified. The system could be some sort of a legacy system (Markosian et al., 1994) where the system is many years old, a current system of which the next release is being produced, or anything in between. The reusable assets will consist of the artifacts from all of the lifecycle phases mentioned previously. This includes, for example: a requirements document, design documents, and code.

The goal in incremental development or maintenance is to perform the given task with least amount of effort while reusing as much as possible from the set of reusable assets. In this section, we discuss a modified form of the software process that takes advantage of UML and meets those needs.

5.1 Process

The software development process from Section 1 must be augmented to allow developers to decide what pieces from the set of the reusable assets are candidates to be reused in the new or evolved system. These pieces could include requirements, design, code, or test plans. Specifically, activities must be added to the process that allows for the understanding of the reusable assets. Figure 5.1 shows the new development process. The activities above the dotted line are the same ones that appeared in Figure 3.1. The activities that appear below the dotted line have been added for the new process. The new activities have been added to take into account the reusable assets when developing the new or evolved system. Before a developer can decide whether or not to use any of the reusable assets, they must first understand those assets. We have found that the UML diagrams can be very useful in this process of understanding.

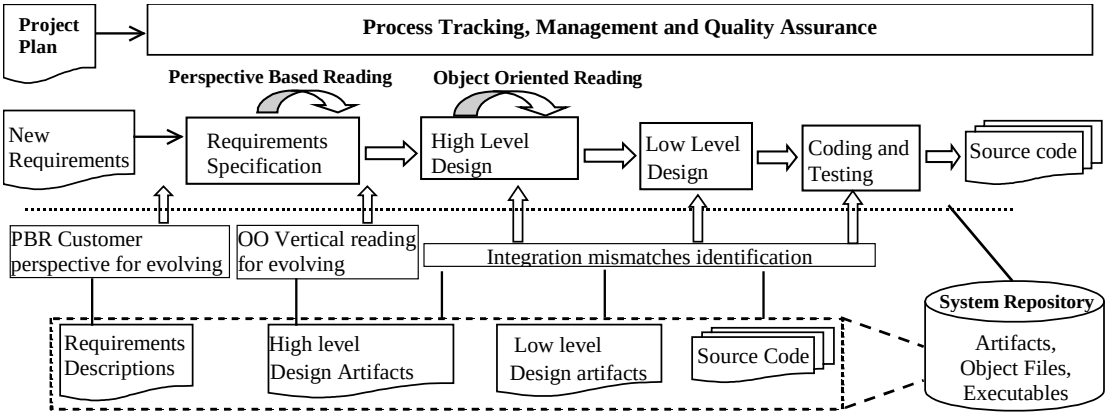


Figure 5.1: Inserting Maintenance activities in the software process

5.2 Understanding

As stated earlier, the goal of the understanding activities is to support the comprehension of the reusable assets. In order for a developer to effectively use the existing requirements or design, s/he must first understand the artifacts themselves, as well as what needs to be done. These understanding activities are important to developers because they allow for the identification of the important pieces from the set of reusable assets that can be (re)used for the new system. Understanding activities should be used for three tasks within the software lifecycle: (1) to understand the old requirements, (2) to understand the old design and (3) to determine what the integration mismatches are.

When a developer is evolving or maintaining a system, in general, there will be more requirements retained from the old system than new ones added. Because of this, it makes sense to reuse as much of the existing requirements as possible. But, before a developer can effectively reuse those requirements they must be understood. When examining the old requirements, developers strive to understand which domain level concepts are present in or absent from those requirements in the context of the new requirements that have been received. The main goal here is to determine, on a high level, if the old set of requirements is in conflict with the new requirements, or if the old requirements can simply be modified to include the new requirements. If the developer can efficiently reuse the existing requirements, it could have a positive effect on the cost and effort of the new system.

Likewise, once the developers have created the new set of requirements, they must examine the existing design with the goal in mind of understanding that design. When developers examine the old design, they need to determine if the way that the domain was represented will allow the new requirements to be added. The old design must be understood from the point of view of whether the earlier design decisions conflict with a newly added requirement, or if the old design allows itself to be modified to include the new requirements. By reading the old design for understanding, the developers acquire enough knowledge to create a design for the new system, reusing as much of the old design as possible. Again, if this reuse is efficient, it could have a positive effect on the cost, effort, and complexity of the new system.

Integration mismatches are a way to describe problems that may be encountered when using COTS. In this case, the reusable assets can be viewed as a COTS. Therefore, the developers must determine if the new design and the reusable assets are compatible. For a more complete discussion of this topic see (Yakimovitch et al., 1999).

Although these types of understanding activities exist in most software life cycles, developers traditionally have accomplished them with little or no guidance. This means that the developers normally examine the artifacts in an ad-hoc fashion and try to identify the features which they consider to be important. From earlier research, we have seen that, in general, developers tend to be more effective at performing an inspection or reading task when using a technique rather than doing it in an unguided fashion. The reason for this is that the techniques help the reader to better focus on the task at hand, and accomplish the important steps necessary for its successful completion.

Earlier in this text we mentioned two techniques, PBR and OORTs, that were designed for use in the process of defect detection. These techniques were defined to be useful with the UML artifacts. As we began to look more closely at this issue and reexamine the techniques, we became aware that those techniques appeared to, with slight modifications, allow the developers to understand the document(s) being inspected, rather than to find defects in the document. In the following sections, we will discuss how PBR and OORTs can be used in the process of understanding for evolving a system.

5.1.1 PBR

The necessary starting point in this process is the requirements. This is because the requirements determine, at the highest level, what pieces of the reusable assets can be reused in the new system. When developing the next version of a system, two important artifacts are present: (1) the set of requirements describing what is to be added to the system, and (2) the requirements and use cases from the existing reusable assets. To begin determining how much of the reusable assets can be reused, the developer must examine these two sets of requirements and use cases to find out where potential discrepancies lie.

This examination can be done by reading the documents. This reading is usually performed in some ad-hoc manner. The Perspective Based Reading techniques that were discussed in Section 4.1.1 for examining a new set of requirements can also be used in this understanding process. A developer can take the new set of requirements and read these against the requirements and use cases from the set of reusable assets to determine where the discrepancies lie. The goal of this is to come up with a new set of requirements that contains both the old and the new requirements. Here only the customer perspective of PBR is used. This is because the type of information that is gathered by this perspective most closely resembles the type of information that is necessary to evolve the requirements.

The main task of the reader here is to determine what has to be ‘fixed’ or changed so that the new requirement can be added to the existing system. There are many situations that the reader is looking for. Using the PBR’s customer perspective, the reader first examines the participants. It must be determined whether the participants in the new system are the same as those in the old system. For example, new participants may need to be added, names of participants may need to be changed for consistency, or the way that a participant interacts with the system may change.

The next thing that readers look at is product functionality. The reader will examine the existing use-cases to determine if they cover the new functionality. If they do not, then either new use-cases must be created, or the old use-cases must be modified to handle the new functionality. The reader also needs to determine if the relationships between the participants, discussed above, and these product functions remain the same in the new system, or if changes must be made. The result of this process is a list of these discrepancies that aids the developers in integrating the new requirements and the set of requirements taken from the reusable assets.

5.1.2 OORT

Once a developer has come up with a new set of requirements describing the new system, the next step is to create a design for this system. Again, this is typically done in some sort of ad-hoc fashion. Here developers are interested in doing similar tasks to what was accomplished in the requirements phase. Now that a set of requirements has been created that includes the new requirements, the UML design documents from the set of reusable assets must be read against this set of requirement to determine where the discrepancies lie.

When we speak of discrepancies here, we are referring, at an abstract level, to the information gap between the old and the new system. This may include the fact that new classes must be added to the design to support the new requirements. Or, new attributes and behaviors may need to be added to existing classes to support the new functionality. The way that classes interact and pass messages may need to be changed also to support the structure of the new system.

> Monthly bill payments will now be accepted using a credit card over the Internet. The customer must access the Gas Station homepage. The customer will log in using his account number and password. The password is assigned by the Gas Station at the time of account creation. The customer is presented with the amount of his current bill. The customer then enters the amount they wish to pay and their credit card information. The credit card information is verified by the system. If verification succeeds, the bill is updated in the system. If it fails, the customer is presented with the reason for failure, and given a chance to try again.

Figure 5.2 – New Gas Station Requirement

The Object Oriented Reading Techniques, and more specifically, the Vertical Reading techniques discussed in Section 3.2.2 are well suited for this task. The reason that Vertical Reading can be used here, is that when performing Vertical Reading, a reader examines a set of requirements against the UML diagrams of a design. The main difference that arises when these

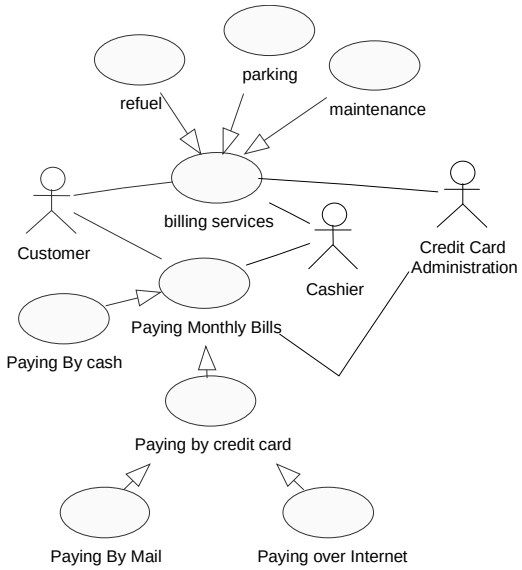
techniques are used to understand the reusable assets is that the reader is looking for discrepancies between the new requirements and the reusable assets. At this point, the reader is not looking for defects, because the requirements and the design are describing two different systems. Rather, the reader is trying to determine what parts of the old design are inconsistent with the new requirements. Once this is determined, the designer can create the design for the new system by using as much of this old design as possible and augmenting or changing where necessary as dictated by the discrepancies.

5.3 Example

In this section, we will show how the process described in this section can be used to extend the example problem presented in Section 4. For the purposes of this example, assume that the Gas Station owner has decided that he now wishes to allow his customers to pay their monthly bills by Credit Card via the Internet as well as via mail. The new requirement can be seen in Figure 5.2.

The first step in creating the evolved system is to apply PBR in order to determine how the set of reusable assets *(*the old set of Gas Station Requirements*)* can be used in conjunction with this new requirement. When PBR is applied, it was determined that the new requirement only requires a minor change to the reusable assets. We found that there is already a requirement that allows for the payment of monthly bills using a credit card. The old system only allowed this payment to be made by mail. So, the new requirement does not change they system, it only extends some functionality that is already present. To include the new requirement in the system we can leave a majority of the requirements unchanged and just add the new functionality. To do this Requirement 7 is the only one that has to change. In Figure 5.3, it has been split into two parts, one dealing with payments by mail (7.1) and the other dealing with payments over the Internet (7.2).

The next step is to examine the use-cases to determine if modifications are necessary. Because a use-case for paying monthly bills by credit card already exists, we can split that use-case into two sub-cases one for payment by mail, and one for payment on the Internet. The new use-cases can be seen in Figure 5.3.



Specific Use Case for "Paying by Credit Card":

Types of Credit Card Payments:

1) Paying By Mail

Customer sends payment and account number to the cashier.
Cashier selects the payment option and enters account number, amount remitted, and type of payment. If any of these information are not entered, payment can not be completed (cashier interface will display a message) and the operation will be cancelled.

Gas Station ask Credit Card System to authorize payment
if authorization is ok payment is made
if payment is not authorized or failed Cashier receives a message describing that payment was not able to be processed. Cashier must repeat operation once more before cancel all the operation.

2) Paying over Internet

Customer logs on to the homepage and account number and password.
System prompts will bill amount.
Customer enters amount to pay and credit card info
Gas Station ask Credit Card system to authorize payment.
If authorization is OK, payment is made
If authorization fails, customer receives message describing that payment could not be made.
Customer my try 1 more time or cancel operation.

Figure 5.3 – Evolved Use Cases

Now that we have the evolved requirements and use cases, the next step is to modify the design so that it includes the new requirements. When applying OORTs we determined that the only change to the class diagram that was needed was to add a new class to model the homepage. We also determined that a new sequence diagram was needed to model the new use case of "Payment over Internet". These new diagrams can been seen in Figure 5.4 and 5.5 respectively.

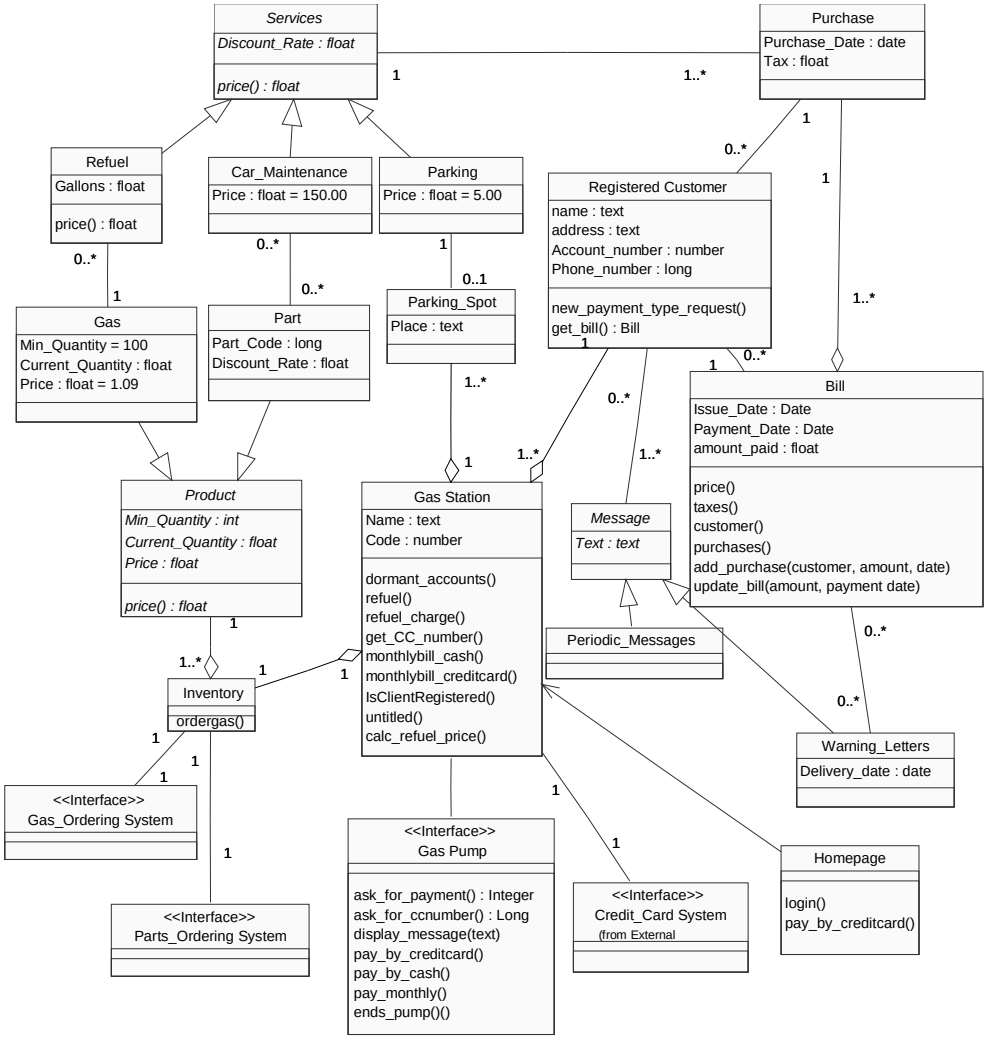


Figure 5.4 – Evolved Class Diagram

6. The Road Ahead

Software design is a great challenge. Increasing product commercialization, rapidly changing technologies, shorter deadlines, the Internet, and other factors are radically changing the software industry daily. Narrow software engineering training is making the design of software a more complex problem each day (Clark, 2000).

Well-engineered software needs good software engineering. Software developers are demanding new techniques and instruments from software engineers to support their software design. Deadlines are constantly short. Quality and productivity needs to be high. Costs must be low. Flexibility for change is necessary to follow technology and users requests. All these factors surround software design.

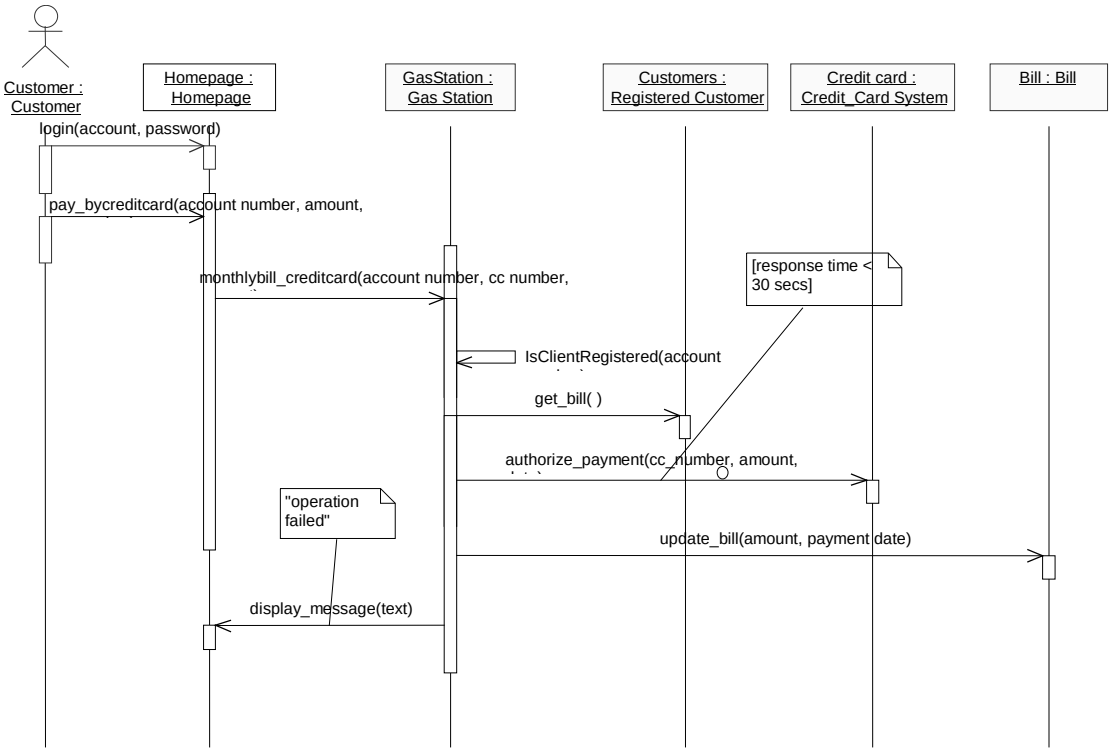


Figure 5.5 – Sequence Diagram

The software design process described in this text tries to deal with some of these issues without building one more complication for designers. Using a standard notation (UML) and a combination of simple techniques (PBR and OORTs) and models (waterfall software life cycle) we described how developers can prepare the design of an application accomplishing a few activities at the same time that can reduce the number of defects. In addition, the same ideas were shown to be useful to evolve or maintain the UML artifacts for a software product.

Although not complete as a software development process it can be tailored to fit in different software processes frameworks or be used as the basis for defining more complete software processes.

Bibliography

Basili, V. R., Briand, L. C. and Melo, W. L. , IEEE Transactions on Software Engineering, A Validation of Object-Oriented Design Metrics as Quality Indicators. Volume 22, Number 10, pp 751-761, October 1996.

Basili, V., Caldiera, G., Lanubile, F., and Shull, F. (1996). Studies on reading techniques. *In Proc. of the Twenty-First Annual Software Engineering Workshop*, SEL-96-002, pages 59-65, Greenbelt, MD, December.

Beizer, B. (1995). Black-Box Testing : Techniques for Functional Testing of Software and Systems. John Wiley & Sons. ISBN 0471120944

Binder, R. V. (1999). Testing Object-Oriented Systems: Models, Patterns, and Tools. Addison-Wesley Pub Co. ISBN 0201809389

Booch, G. (1994). Object-Oriented Analysis and Design, Prentice-Hall.

Booch, G. (1999). UML in Action, Communications of the ACM, vol. 42, No. 10, pp. 26-28, October.

Booch, G.; Rumbaugh, J. and Jacobson, I. (1999). The Unified Modeling Language User Guide. Addison-Wesley Object Technology Series. Addison-Wesley. ISBN 0201571684.

Buschmann, F.; Meunier, R.; Rohnert, H., Sommeerlad, P. and Stahl, M. (1996). Pattern-Oriented Software Architecture: A System of Patterns. New York: John Wiley and Sons.

Cangussu, J.W.L.; Penteado, R.A.D. ; Masiero, P.C.; Maldonado, J.C. (1995). Validation of Statecharts Based on Programmed Execution, Journal of Computing and Information, Vol. 1 (2), ISSN 1201-8511 (CD-ROM Issue), Special Issue of the Proceedings of the 7th International Conference on Computer and Information ICCI'95, Peterborough, Ontario, CA, July.

Chidamber, S.R. and Kemerer, C. F. (1994). A Metrics Suite for Object Oriented Design, IEEE Transactions on Software Engineering, vol.20, number 6, June.

Clark, D. (2000). Are Too Many Programmers Too Narrowly Trained?. IEEE Computer, vol. 33 number 6, pp. 12-15, June.

Coad, P. and Yourdon, E. (1991). Object-Oriented Design. Yourdon Press Computing Series. ISBN: 0136300707

Coleman , D.; Bodoff, S. and Arnold, P. (1993). Object-Oriented Development: The Fusion Method. Prentice Hall; ISBN 0-133-38823-9.

Conallen, J. (1999). Modeling Web Application Architectures with UML. Communications of the ACM, vol. 42, number 10, pp. 63-70, October.

Clunie, C.; Werner, C.; Rocha, A. (1996). How to Evaluate the Quality of Object-Oriented Specifications. 6th International Conference on Software Quality. Ottawa, Canada, pp.283-293.

Chung, L.; Nixon, B. A.; Yu, e. and Mylopoulos, J. (1999). Non-Functional Requirements in Software Engineering. Kluwer Academic Publishers. ISBN 0792386663.

Delamaro, M. E. and Maldonado, J.C. (1996). Integration Testing Using Interface Mutation. VII International Symposium on Software Reliability Engineering (ISSRE), White Plains - NY, pp 112-121, November.

Douglass, B. P. (1999). Doing Hard Time: Developing Real-Time Systems with UML, Objects, Frameworks and Patterns**,** Addison-Wesley Pub Co; ISBN: 0201498375

D'Souza, D. F. and Wills, A. C. (1998). Objects, Components, and Frameworks With UML : The Catalysis Approach. Addison-Wesley Pub Co; ISBN 0201310120

Eriksson, H. and Penker, M. (1997). UML Toolkit. John Wiley & Sons; ISBN 0471191612.

Epstein, P. and Sandhu, R. (1999). Towards a UML based approach to role engineering. Proceedings of the fourth ACM workshop on role-based access control on Role-based access control, pp. 135-143. October, Fairfax, VA USA

Evans, A. and Kent, S. (1999). Core Meta-Modeling Semantics of UML: The pUML Approach. In the Proceedings of the Second International Conference on the Unified Modeling Language - UML'99. Fort Collins, Colorado, USA.

Fagan, M., (1976). Design and code inspections to reduce errors in program development. IBM Systems Journal, 15(3):182-211

Finkelstein, A.; Krammer, J. and Nuseibeth, B. (eds.) (1994). Software Process Modeling and Technology, John Wiley and Sons Inc.

Fowler, M. and Scott, K. (2000). UML Distilled: A Brief Guide to the Standard Object Modeling Language, Second Edition, Addison-Wesley. ISBN 020165783X

Gamma, E.; Helm, R.; Johnson, R. and Vlissides, J. (1995). Design Patterns: Elements of Reusable Object-Oriented Software. Addison-Wesley.

Gilb, T. and Graham, D. (1993). *Software Inspection*. Addison-Wesley, Reading, MA.

Graham, I. M.; Henderson-Sellers, B. and Younessi, H. (1997). The OPEN Process Specification, Addison-Wesley, Harlow, UK.

Harel, D. and Naamad, A. (1996). The STATEMATE semantics of statecharts. ACM Transactions on Software Engineering and Methodology. Volume 5, Issue 4, pp. 293-333.

Henderson-Sellers, B. (1996). Object-Oriented Metrics: Measures of Complexity. Prentice Hall, Inc. ISBN 0132398729.

IEEE Std 830-1993. (1993). Recommended Practice for Software Requirements Specifications. New York: Software Engineering Standards Committee of the IEEE Computer Society.

IEEE (1987). Software Engineering Standards. IEEE CS Press.

Jacobson, I.; Christerson, M.; Jonsson, P. and Övergaard, G. (1992). Object-Oriented Software Engineering: A Use Case Driven Approach. (revised printing). Addison-Wesley

Jacobson, I.; Booch, G. and Rumbaugh, J. (1999). The Unified Software Development Process. Addison-Wesley, ISBN 0201571684.

Jäger, D.; Schleicher, A. and Westfechtel, B. (1999). Using UML for Software Process Modeling. Proceedings of the 7th European Engineering Conference held jointly with the 7th ACM SIGSOFT symposium on Foundations of Software Engineering, pp. 91-108. September, Toulouse France.

Jalote, P. (1997). An Integrated approach to Software Engineering. Second Edition. Springer. ISBN 0387948996

Juristo, N., Moreno, A. M. and López, M. (2000). How to Use Linguistic Instruments for Object-Oriented Analysis. IEEE Software, pp. 80-89, May/June

Kitchenham, B. A.; Travassos, G.H., von Mayrhauser, A.; Niessink, F.; Shneidewind, N. F., Singer, J., Takada, S., Vehvilainen, R., Yang, H. (1999). Towards an Ontology of

Software Maintenance, Journal of Software Maintenance: Research and Practice, volume 11, issue 6, pp. 365-389, John Wiley & Sons.

Kobryn, C. (1999). UML 2001: A Standardization Odyssey. Communications of the ACM, vol. 42, number 10, pp. 29-37, October.

Krutchen, P. (1999) The Rational Unified Process: An Introduction, Addison-Wesley, Reading, Mass.

Kung, C.; Hsia, P.; Gao, J. and Kung, D. C. (1998).Testing Object-Oriented Software. October, IEEE Computer Society ISBN 0818685204

Larsen, G. (1999). Designing Component-Based Frameworks Using Patterns in the UML. Communications of the ACM, vol. 42, number 10, pp. 38-45, October.

Leite, J. C. S. P. and Freeman, P. A. (1991). Requirements Validation Through Viewpoint Resolution. IEEE Transactions on Software Engineering: Vol. 17, N. 1, pp. 1253-1269.

Lie, W. and Henry, S. (1993). Object-oriented metrics that predict maintainability, Journal of Systems and Software. 23(2):111-122.

Lorenz, M., and J. Kidd (1994). Object-Oriented Software Metrics, Prentice-Hall.

Lockman, A. and Salasin, J. (1990). A procedure and tools for transition engineering. Proceedings of the fourth ACM SIGSOFT symposium on Software development environments, pp. 157-172. December, Irvine, CA USA.

Markosian, L.; Newcomb, P.; Brand, R.; Burson, S. and Kitzmiller, T. (1994). Using an enabling technology to reengineer legacy systems. Communications of the ACM. Volume 37, Issue 5, Pages 58-70.

Meyer, B. (1997). Object-Oriented Software Construction. Second Edition. Prentice-Hall. ISBN 0-13-629155-4

Morisio, M., Travassos, G. H. and Stark, M. (2000). Extending UML to support Domain Analysis. In the Proceedings of the 15th IEEE International Conference on Automated software Engineering. Grenoble, France, September.

NASA. (1993). National Aeronautics and Space Administration, Office of Safety and Mission Assurance. "Software Formal Inspections Guidebook". Report NASA-GB-A302, August 1993.

Offutt, J. (1995). Practical Mutation Testing. Twelfth International Conference on Testing Computer Software, pages 99--109, Washington, DC, June.

Offutt, J. and Abdurazik, A. (1999). Generating Tests from UML Specifications. *Second International Conference on the Unified Modeling Language (UML99)*, Fort Collins, CO, October.

OMG - Object Management Group, Inc. (1999). UML V1.3 - Unified Modeling Language Specification, Version 1.3. June (http://www.omg.org)

Perry, W. (2000). Effective Methods for Software Testing. John Wiley and Sons, Inc. 2nd Edition. ISBN 047135418X

Pfleeger, S. (1998). Software Engineering: Theory and Practice. Prentice-Hall. ISBN 013624842X

Pressman, R. (1997). Software Engineering: A Practitioner's Approach. Fourth Edition. McGraw-Hill. ISBN 0070521824

Porter, A., Votta Jr., L., Basili, V. (1995). Comparing Detection Methods for Software Requirements Inspections: A Replicated Experiment. *IEEE Transactions on Software Engineering*, 21(6): 563-575, June.

Rumbaugh, J.; Blaha, M.; Premerlani, W.; Eddy, F. and Lorenson, W.(1992). Object-Oriented Modeling and Design. Prentice-Hall. ISBN 0136298419

Rumbaugh, J.; Jacobson, I. and Booch, G. (1999). The Unified Modeling Language Reference Manual. Addison-Wesley Object Technology Series. Addison-Wesley. ISBN 020130998X.

Selic, B. (2000). A Generic Framework for Modeling Resources with UML, IEEE Computer, pp. 64-69, June.

Shroff, M. and France, R.B. (1997). Towards a formalization of UML class structures in Z. In the Proceedings of the COMPSAC'97 - 21st International Computer Software and Applications Conference.

Shull, F.; Travassos, G. H.; Carver, J. and Basili, V. R. (1999). Evolving a Set of Techniques for OO Inspections. Technical Report CS-TR-4070, UMIACS-TR-99-63, University of Maryland, October. On line at http://www.cs.umd.edu/Dienst/UI/2.0/Describe/ncstrl.umcp/CS-TR-4070

Travassos, G. H.; Andrade, R. S. (1999). Combining Metrics, Principles and Guidelines for Object Oriented Complexity Reduction, Workshop on Quantitative Approaches in Object Oriented Software Engineering, ECOOP'99, Lisbon, Portugal, June.

Travassos, G.; Shull, F.; Fredericks, M. and Basili, V. (1999). Detecting Defects in Object-Oriented Designs: Using Reading Techniques to Improve Software Quality. In the Proceedings of the Conference on Object-Oriented Programming, Systems, Languages, and Applications (OOPSLA), Denver, Colorado, 1999.

Uemura, T.; Kusumoto, S. and Inoue, K. (1998). Function Point Measurement Tool for UML Design Specification. In the Proceedings of the 6th International Symposium on Software Metrics.

van Solingen, R. and Berghout, E. (1999). The Goal/Question/Metric Method: A Practical Guide for Quality Improvement of Software Development. McGrawn Hill. ISBN 0077095537

Vieira, M. E. R. and Travassos, G. H. (1998). An Approach to Perform Behavior Testing in Object-Oriented Systems, Proceedings of the Technology of Object-Oriented Languages - TOOLS 27, Beijing, China, IEEE Computer Society, ISBN 0-8186-9096-8

Votta Jr., L. G. (1993). Does Every Inspection Need a Meeting?. *ACM SIGSOFT Software Engineering Notes*, 18(5): 107-114, December.

Yakimovitch, D.; Travassos, G. H. and Basili, V. R. (1999). A Classification of Components Incompatibilities for COTS Integration**,** 24th Annual Software Engineering Workshop, NASA/SEL, Greenbelt, USA, Dezembro, 1999.

Warmer, J. B. and Kleppe, Anneke G. (1999). Object Constraint Language : Precise Modeling With Uml. Addison-Wesley Pub Co. ISBN 0201379406.

Wirfs-Brock, R., Wilkerson, B. and Wiener, L. (1990). Designing Object-Oriented Software. Prentice Hall; ISBN 0136298257.