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WepSIM: Simulador de procesador elemental con unidad de control microprogramada

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*Insanity: doing the same thing over and over
again and expecting different results.*

Albert Einstein

Agradecimientos

Por agradecer ...

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microprogramada**

by

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Abstract

Keywords: MIPS · Simulation · Assembler · Microprogramming

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Chapter 1

Introducción

El primer capítulo introduce brevemente el objetivo del proyecto, incluyendo las características clave del proyecto y su motivación (Section 1.1, *Motivación*), los objetivos del proyecto (Section 1.2, *Objetivos*), y toda la estructura del documento (Section 1.3, *Estructura del documento*).

1.1 Motivación

Hay distintos simuladores que se pueden utilizar para trabajar con los principales aspectos que se tratan en las asignaturas de Estructura y Arquitectura de Computadores: ensamblador, caché, etc. Aunque la idea de usar distintos simuladores cae dentro de la estrategia de "divide y vencerás", hay dos principales problemas con estos simuladores: cuanto más realistas son más compleja se hace la enseñanza (tanto del simulador como de la tarea simulada), y cuantos más simuladores se usan más se pierde la visión de conjunto.

Hay otro problema no menos importante: la mayoría de los simuladores están pensados para PC. Uno de los objetivos que nos planteamos con WepSIM es que pudiera ser utilizado en dispositivos móviles (smartphones o tablets), para ofrecer al estudiante una mayor flexibilidad en su uso.

Además de tener un simulador portable a distintas plataformas, el simulador ha de ser lo más autocontenido posible de manera que integre la ayuda principal para su uso (no como un documento separado que sirva de manual de uso para ser impreso) permitiendo al usuario hacer un uso completo de la aplicación sin la necesidad de salir de ella.

Por todo ello, nos hemos planteado cómo ofrecer un simulador que sea simple y modular, y que permita integrar la enseñanza de la microprogramación con la programación en ensam-

blador. En concreto, puede utilizarse para microprogramar un juego de instrucciones y ver el funcionamiento básico de un procesador, y para crear programas en ensamblador basados en el ensamblador definido por el anterior microcódigo. Esto es de gran ayuda, por ejemplo, para la programación de sistemas dado que es posible ver cómo interactúa el software en ensamblador con el hardware en el tratamiento de interrupciones. La idea es ofrecer un simulador que ofrezca una visión global de lo que pasa en hardware y software, evitando además el tiempo extra que supone el aprendizaje de distintas herramientas.

1.2 Objetivos

El objetivo principal de este proyecto, es desarrollar un simulador, que a diferencia de los existentes, pueda simular de forma completa el comportamiento de un procesador elemental permitiendo comprobar el estado de los componentes en cada ciclo de reloj, de manera que ayude a los alumnos a comprender y asimilar de forma sencilla y visual el funcionamiento de un procesador. Los objetivos secundarios son:

- Diseñar la especificación del juego de instrucciones que permita la creación de un lenguaje ensamblador adaptado a la arquitectura del simulador.
- Diseñar e implementar el compilador del juego de instrucciones para la generación del firmware del simulador.
- Diseñar e implementar el compilador genérico de ensamblador que permita la generación del binario correspondiente al juego de instrucciones diseñado.
- Diseñar e implementar el motor del simulador permitiendo ejecuciones reales del código ensamblador correspondiente al juego de instrucciones compilado.
- Diseñar una interfaz que proporcione en todo momento la información necesaria en relación al estado de la ejecución del código, de forma sencilla y visual.
- Permitir que los usuarios puedan importar/exportar tanto la especificación del juego de instrucciones como el código ensamblador.
- Crear un mecanismo de "modificación en caliente" que permita en mitad de una ejecución modificar el juego de instrucciones, de forma que se puedan realizar pruebas sin necesidad de reiniciar la ejecución.

1.3 Estructura del documento

El documento contiene los siguientes capítulos:

- Capítulo 1, *Introducción*, presenta una breve descripción del contenido del documento. También incluye la motivación y los objetivos del proyecto.
- Capítulo 2, *Estado del arte*, incluye una descripción de los diferentes tipos de simuladores de lenguaje ensamblador y simuladores de microcódigo y presenta el trabajo relacionado.
- Capítulo 3, *Análisis*, describe brevemente el proyecto, explica la solución elegida, establece los requisitos y presenta el marco regulador del proyecto.
- Capítulo 4, *Diseño*, detalla el diseño del sistema, incluyendo todos sus componentes.
- Capítulo 5, *Implementación y despliegue*, incluye los detalles de implementación de las partes principales del software desarrollado y las características necesarias para la implementación de la aplicación.
- Capítulo 6, *Verificación, validación y evaluación*, detalla una verificación y validación completa del proyecto. También muestra una evaluación de diferentes casos de prueba utilizando el simulador.
- Capítulo 7, *Planificación y presupuesto*, presenta los conceptos relacionados con la planificación seguida, descompone todos los costes del proyecto y describe el entorno socio-económico.
- Capítulo 8, *Conclusiones y trabajos futuros*, incluye las contribuciones del proyecto, explica las principales conclusiones del proyecto y presenta los trabajos futuros.
- Appendix A, *User Manual*, incluye un manual de usuario completo para la aplicación. Contiene un tutorial que guía al usuario desde la creación de un nuevo juego de instrucciones hasta una ejecución completa paso a paso, y una serie de ejemplos educativos para aprender el funcionamiento de un procesador mediante el uso de simulaciones utilizando el software desarrollado.

Chapter 2

Estado del arte

Este capítulo presenta el estado del arte, la última y más avanzada etapa de las tecnologías relacionadas con nuestra aplicación. Primero, se presentan los diferentes simuladores existentes para microprogramación (Section 2.1). Después, se presentan los diferentes simuladores existentes para la programación en código ensamblador (Section 2.2). Por último, realizamos una comparación de nuestro trabajo con el contexto actual de los distintos simuladores expuestos previamente (Section 2.3).

2.1 Simuladores para microprogramación

En esta sección, se explican los diferentes simuladores existentes para la microprogramación. En primer lugar, vamos a centrarnos en los simuladores que están más enfocados a una labor docente.

2.2 Simuladores para programación en ensamblador

En esta sección, se explican los diferentes simuladores existentes para la programación en ensamblador. Los simuladores más conocidos para labores docentes, son SPIM, MARS y WebMIPS.

SPIM [1], es un simulador de un procesador MIPS de 32 bits desarrollado a principios de 1990. En un primer momento implementaba el juego de instrucciones MIPS-1, utilizado por los computadores MIPS R2000/R3000. Actualmente, implementa la arquitectura MIPS32 más reciente y sus instrucciones adicionales. Permite ejecutar programas en ensamblador para esta

arquitectura. Además, también permite depurar el código implementado, de forma que el alumno pueda corregir con mayor facilidad los errores cometidos. Este simulador, fue creado por James R. Larus y tiene versiones compiladas para Windows, Mac OS X y Unix/Linux e incluso tiene una versión básica para Android, aunque su diseño no está pensado para dispositivos móviles. Puesto que el simulador está totalmente enfocado al procesador MIPS, posee el juego completo de instrucciones para la versión de 32 bits del procesador y todas las directivas de las que consta el lenguaje. Otra característica que hace de SPIM un potente simulador, es proveer de un pequeño sistema operativo que soporta las principales llamadas al sistema mediante la instrucción syscall. SPIM, es un simulador que permite múltiples configuraciones mediante su interfaz de usuario, de manera que se puede indicar:

- Activación del uso de pseudoinstrucciones.
- Simulación de predicción de saltos y accesos a memoria, con la latencia correspondiente.
- Activación del uso del manejador de la señal trap y la carga del manejador personalizado.
- Activación de la visualización de los mensajes en caso de ocurrir excepciones.
- Activación del uso de "memory-mapped IO".

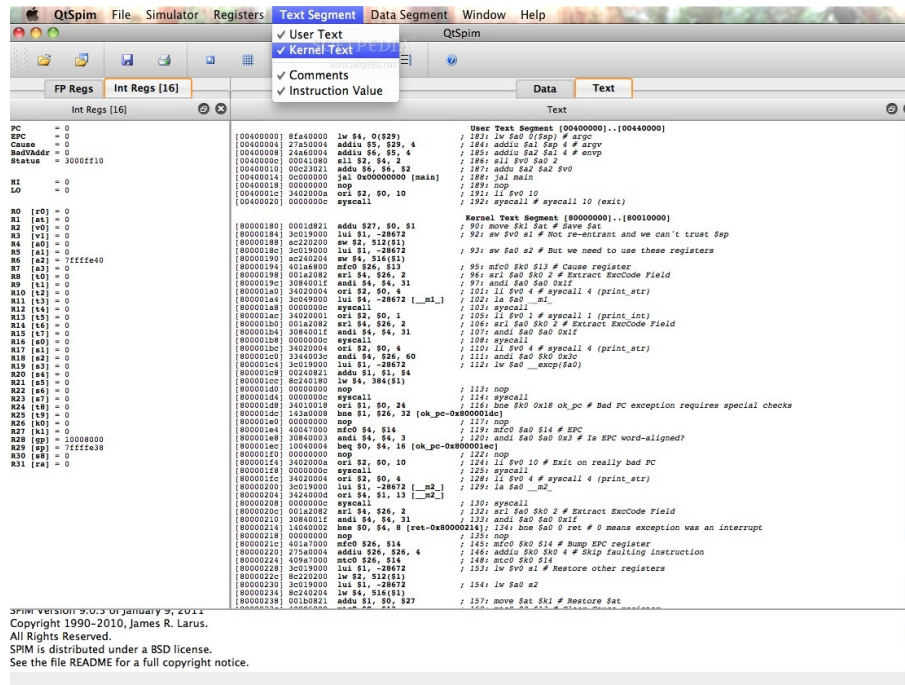
SPIM, además cuenta con una versión más actualizada del simulador, que posee una interfaz gráfica más potente. Éste simulador se llama QtSPIM [2], y cuenta con todas las características anteriormente mencionadas de SPIM.

MARS [3], es un simulador con interfaz gráfica desarrollado en JAVA para el lenguaje ensamblador MIPS. Fue creado en el año 2005 como una alternativa del simulador SPIM y diseñado específicamente para las necesidades limitadas de cursos de pregrado. Está basado en la arquitectura MIPS RISC, que tiene un número pequeño de elementos del lenguaje e instrucciones. Consta de operaciones de entrada/salida, saltos, condiciones y operaciones aritmético-lógicas tanto enteras como en coma flotante. Algunas de las mejoras que incorpora MARS con respecto a SPIM son [4]:

- Depuración más sencilla y cómoda, debido a constar de GUI. Ésto se debe, a que para añadir un punto de ruptura, únicamente hay que clickar sobre un checkbox que tiene la instrucción.

xsplm	
Register Display	PC = 00000000 EPC = 00000000 Cause = 00000000 BadVaddr = 00000000 Status= 00000000 HI = 00000000 LO = 00000000 General Registers R0 (r0) = 00000000 R8 (t0) = 00000000 R16 (s0) = 00000000 R24 (t8) = 00000000 R1 (at) = 00000000 R9 (t1) = 00000000 R17 (s1) = 00000000 R25 (s9) = 00000000 R2 (v0) = 00000000 R10 (t2) = 00000000 R18 (s2) = 00000000 R26 (k0) = 00000000 R3 (v1) = 00000000 R11 (t3) = 00000000 R19 (s3) = 00000000 R27 (k1) = 00000000 R4 (a0) = 00000000 R12 (t4) = 00000000 R20 (s4) = 00000000 R28 (gp) = 00000000 R5 (a1) = 00000000 R13 (t5) = 00000000 R21 (s5) = 00000000 R29 (gp) = 00000000 R6 (a2) = 00000000 R14 (t6) = 00000000 R22 (s6) = 00000000 R30 (s8) = 00000000 R7 (a3) = 00000000 R15 (t7) = 00000000 R23 (s7) = 00000000 R31 (ra) = 00000000 Double Floating Point Registers FP0 = 0.000000 FP8 = 0.000000 FP16 = 0.000000 FP24 = 0.000000 FP2 = 0.000000 FP10 = 0.000000 FP18 = 0.000000 FP26 = 0.000000 FP4 = 0.000000 FP12 = 0.000000 FP20 = 0.000000 FP28 = 0.000000 FP6 = 0.000000 FP14 = 0.000000 FP22 = 0.000000 FP30 = 0.000000 Single Floating Point Registers
	<div> <div>quit</div> <div>load</div> <div>run</div> <div>step</div> <div>clear</div> <div>set value</div> </div> <div> <div>print</div> <div>breakpt</div> <div>help</div> <div>terminal</div> <div>mode</div> </div>
	Text Segments
	[0x00400000] 0x8fa40000 lw R4, 0(R29) [] [0x00400004] 0x27a50004 addiu R5, R29, 4 [] [0x00400008] 0x24a60004 addiu R6, R5, 4 [] [0x0040000c] 0x00041090 sll R2, R4, 2 [0x00400010] 0x00c23021 addu R6, R6, R2 [0x00400014] 0x0c000000 jal 0x00000000 [] [0x00400018] 0x34020003 ori R0, R0, 10 [] [0x0040001c] 0x0000000c syscall
	Data Segments
	[0x10000000] ... [0x10010000] 0x00000000 [0x10010004] 0x74705563 0x206e6f69 0x636f2000 [0x10010010] 0x72727563 0x61206465 0x6920646e 0x726f6e67 [0x10010020] 0x000a6465 0x495b2020 0x7265746e 0x74707572 [0x10010030] 0x0000209d 0x20200000 0x616e655b 0x6e67696e [0x10010040] 0x61206465 0x65726464 0x69207373 0x6e69206e [0x10010050] 0x642f7473 0x20617461 0x63746566 0x00205d68 [0x10010060] 0x555b2020 0x696e616e 0x64656e67 0x64646120 [0x10010070] 0x73736572 0x206e6920 0x726f7473 0x00205d65
	SPIM Version 3.2 of January 14, 1990
	SPIM Messages

Figure 2-1: SPIM interface.

Figure 2-2: *QtSPIM interface.*

- Los programas pueden ejecutarse de forma inversa, lo que permite volver a un estado anterior de la máquina en la ejecución de un programa.
- La velocidad de ejecución puede modificarse, de forma que si se ralentiza el usuario puede observar como cada instrucción se resalta cuando está siendo ejecutada y ver los cambios que se producen en los valores del banco de registros y de las ubicaciones de memoria.
- La memoria y los registros se pueden modificar de una manera WYSIWYG.
- Incorpora un editor de texto, eliminando dependencias externas para el uso del simulador.
- Permite que los desarrolladores puedan suministrar nuevos complementos, que por ejemplo, sirvan para extender la arquitectura o mostrar los datos de forma intuitiva.

WebMIPS [5], es un simulador desarrollado en la Facultad de Ingeniería de la Información de Sienna, Italia. Está escrito en el lenguaje de programación ASP.NET y se utiliza mediante una página web, de forma que no requiere de su instalación en local. No soporta el juego completo de instrucciones de MIPS, sino que consta de un juego reducido de instrucciones que sirve de introducción al estudio de arquitectura de computador. Con respecto a los anteriores

simuladores mencionados, difiere al mostrar el esquema arquitectónico, indicando las 5 etapas de pipeline de las que consta el computador que simula. Otra característica, es la indicación del número de ciclos de reloj que consume la ejecución del programa.

2.3 Propuesta de simulación unificada

Chapter 3

Análisis

El objetivo principal de este capítulo, es describir el proyecto mediante la obtención y especificación de los requisitos del simulador, que puede proporcionar información suficiente para un análisis detallado que, por lo tanto, puede servir para continuar diseñando e implementando (Capítulos 4, *Diseño*; and 5, *Implementación y despliegue*) un software que cumpla con esos requisitos.

Con el fin de obtener los requisitos del sistema, el tutor ha desempeñado el papel del cliente en diferentes reuniones, mientras que el alumno ha desempeñado los roles de analista, diseñador, programador y probador.

La sección 3.1 resume brevemente la descripción del proyecto. La sección 3.2 discute la solución elegida y la compara con las alternativas consideradas. La sección 3.3 especifica los requisitos del sistema, empezando con los requisitos de usuario y finalizando con los requisitos funcionales y no-funcionales. Finalmente, la sección 3.4 indica el conjunto de leyes y regulaciones para la gestión del software.

3.1 Descripción del proyecto

Explicamos lo que se pretende obtener del simulador.

3.2 Solución elegida

Explicamos el porque hemos elegido esta solución, y nos comparamos.

Features	SimGrid	PVMsim	Virtual-GEMS	MDCSim	SPECI-2
Languages	C/C++/Java/Ruby	C	C/C++/Ruby	C++/Java	Java
Open Source	✓	✓	✓	✗	✓
Models					
Communication	✓	✗	✗	✓	✓
Energy	✓	✗	✗	✓	✗
Hardware	✓	✓	✓	✓	✓
Scheduling	✓	✓	✗	✗	✓
Users	✓	✗	✗	✓	✗

Table 3.1: *Comparison of simulation frameworks for distributed computing systems.*

3.3 Requisitos

This section provides a detailed description of the application requirements. For the requirement specification task, the IEEE recommended practices [6] were followed. According to these practices, a good specification must address the software functionality, performance issues, the external interfaces, other non-functional features and design or implementation constraints. Moreover, the requirements specification must be:

- **Complete:** the document reflects all significant software requirements.
- **Consistent:** requirements must not generate conflicts with each other.
- **Correct:** every requirement is one that the software shall meet according to the user needs.
- **Modifiable:** the structure of the specification allows changes to the requirements in a simple, complete and consistent way.
- **Ranked based on importance and stability:** every requirement must indicate its importance and its stability.
- **Traceable:** the origin of every requirement is clear and it can be easily referenced in further stages.
- **Unambiguous:** every requirement has a single interpretation.
- **Verifiable:** every requirement must be verifiable, that is, there exists some process to verify that the software complies with every single requirement.

Starting from the user requirements, which constitute an informal reference to the product performance that the client expects, we derived the software requirements (in this case, functional requirements and non-functional requirements) that guided the design process with specific information on the functionality of the system and other characteristics. The retrieved requirements were structured according with the following schema:

1. User Requirements

- (a) **Capacity:** the requirement describes the expected system functionality as in use cases.
- (b) **Restriction:** the requirement specifies constraints or conditions the system must fulfil.

2. Software Requirements

(a) Functional

- i. **Functional:** the requirement describes the basic system functionality and purpose while minimizing ambiguity.
- ii. **Inverse:** the requirement limits the functionality of the application to clarify its scope.

(b) Non-Functional

- i. **Performance:** the requirement is related to the minimum required performance of the resulting system.
- ii. **Interface:** the requirement is related to the user interface of the application.
- iii. **Scalability:** the requirement is related to the ability of the system to adapt to increasing workloads.
- iv. **Platform:** the requirement specifies the underlying software and hardware platforms in which the system will operate.

Table 3.2 provides the template used for requirements specification. Note that for user requirements, the ID format will be UR-XY, where X indicates the requirement subtype: capacity requirements (C), or restrictions (R). Y corresponds to the requirement number under its subcategory. For software requirements, the ID format SR-X-YZZ will be used, where X indicates if it is a functional (F) or non-functional (NF) requirement, and Y represents its subcategory:

functional (F), inverse (I), performance (P), interface (UI), scalability (S), or platform (PL). ZZ corresponds to the requirement number under its subcategory.

ID	Requirement ID.
Name	Requirement name.
Type	Indicates the category in which the requirement would be placed according to the previously described schema.
Origin	Constitutes the requirement source. It might be the user, another requirement or other stakeholders involved in the project.
Priority	Indicates the requirement priority according to its importance. A requirement can be identified either as <i>essential</i> , <i>conditional</i> or <i>optional</i> .
Stability	Indicates the requirement variability through the development process, defined as <i>stable</i> or <i>unstable</i> .
Description	Detailed explanation of the requirement.

Table 3.2: *Template for requirements specification.*

3.3.1 Requisitos de Usuario

This subsection specifies the user requirements.

ID	UR-C01
Name	BOINC projects simulation
Type	Capacity
Origin	User
Priority	Essential
Stability	Stable
Description	The application shall simulate real BOINC projects.

Table 3.3: *User requirement UR-C01.*

ID	UR-C02
Name	Client scheduling
Type	Capacity
Origin	User
Priority	Essential
Stability	Stable
Description	The client scheduler of the simulator shall follow the actual BOINC client scheduling.

Table 3.4: *User requirement UR-C02.*

ID	UR-C03
Name	Simulation components
Type	Capacity
Origin	User
Priority	Essential
Stability	Stable
Description	The simulations shall cover all the elements present in the BOINC infrastructure.

Table 3.5: *User requirement UR-C03.*

ID	UR-R01
Name	Linux as underlying OS
Type	Restriction
Origin	User
Priority	Essential
Stability	Stable
Description	The simulator shall be designed for Linux operating systems.

Table 3.6: *User requirement UR-R01.*

ID	UR-R02
Name	SimGrid toolkit
Type	Restriction
Origin	User
Priority	Essential
Stability	Stable
Description	The application shall use the SimGrid toolkit in order to implement the distributed computing functionalities.

Table 3.7: *User requirement UR-R02.*

ID	UR-R03
Name	Scalability
Type	Restriction
Origin	User
Priority	Essential
Stability	Stable
Description	The simulator shall be scalable (carry out executions by simulating a large number of client hosts).

Table 3.8: *User requirement UR-R03.*

3.3.2 Requisitos Funcionales

This subsection specifies the functional requirements.

ID	SR-F-F01
Name	Credit calculation
Type	Functional
Origin	UR-C01
Priority	Essential
Stability	Stable
Description	The simulator shall calculate the number of credits granted to each volunteer client analogously to actual BOINC projects.

Table 3.9: *Functional requirement SR-F-F01.*

ID	SR-F-F02
Name	Collection of statistics
Type	Functional
Origin	UR-C01
Priority	Essential
Stability	Stable
Description	The simulator shall collect, for each project, the same statistics that actual BOINC projects (published in BOINCstats [7]).

Table 3.10: *Functional requirement SR-F-F02.*

ID	SR-F-F03
Name	Almost identical outputs
Type	Functional
Origin	UR-C01
Priority	Essential
Stability	Stable
Description	The outputs of the simulator for existing projects should be almost identical to those published in BOINCstats [7].

Table 3.11: *Functional requirement SR-F-F03.*

ID	SR-F-F04
Name	Multiple BOINC projects
Type	Functional
Origin	UR-C01
Priority	Essential
Stability	Stable
Description	The simulator shall allow the simulation of different projects simultaneously.

Table 3.12: *Functional requirement SR-F-F04.*

ID	SR-F-F05
Name	Client scheduler
Type	Functional
Origin	UR-C02
Priority	Essential
Stability	Stable
Description	The client scheduler shall follow the actual BOINC client scheduling (described in [8]).

Table 3.13: *Functional requirement SR-F-F05.*

ID	SR-F-F06
Name	Realistic simulation elements
Type	Functional
Origin	UR-C03
Priority	Essential
Stability	Stable
Description	All simulations shall include the following elements: tasks, volunteer hosts, servers, data servers, networks, and hosts availability.

Table 3.14: *Functional requirement SR-F-F06.*

3.3.3 Requisitos No-Funcionales

This subsection specifies the non-functional requirements.

ID	SR-NF-PL01
Name	Ubuntu 14.04
Type	Platform
Origin	UR-R01
Priority	Essential
Stability	Stable
Description	The simulator shall work on the Ubuntu Linux distribution, version 14.04.

Table 3.15: *Non-functional requirement SR-NF-PL01.*

ID	SR-NF-PL02
Name	SimGrid MSG API
Type	Platform
Origin	UR-R02
Priority	Essential
Stability	Stable
Description	The implementation, setup and control of the simulations shall be carried out using the MSG API of the SimGrid toolkit.

Table 3.16: *Non-functional requirement SR-NF-PL02.*

ID	SR-NF-PL03
Name	C programming language
Type	Platform
Origin	UR-R03
Priority	Essential
Stability	Stable
Description	The simulator shall be written in the C programming language.

Table 3.17: *Non-functional requirement SR-NF-PL03.*

ID	SR-NF-S01
Name	Large simulations
Type	Scalability
Origin	UR-R03
Priority	Essential
Stability	Stable
Description	The application must be able to perform simulations with more than 100,000 hosts in a machine with at least 8 GB of Random-Access Memory (RAM).

Table 3.18: *Non-functional requirement SR-NF-S01.*

ID	SR-NF-P01
Name	Linear-time execution
Type	Performance
Origin	UR-R03
Priority	Conditional
Stability	Stable
Description	Runtime of the simulator must be linear (approximately) in the number of hosts.

Table 3.19: *Non-functional requirement SR-NF-P01.*

ID	SR-NF-UI01
Name	Simulation parameters
Type	Interface
Origin	Analyst
Priority	Essential
Stability	Stable
Description	To perform simulations, users only need to specify the simulation parameters in an Extensible Markup Language (XML) file.

Table 3.20: *Non-functional requirement SR-NF-UI01.*

ID	SR-NF-UI02
Name	Progress bar
Type	Interface
Origin	Analyst
Priority	Conditional
Stability	Stable
Description	The simulations should include a progress bar.

Table 3.21: *Non-functional requirement SR-NF-UI02.*

3.4 Marco Regulator

This section discusses the necessary constraints taking into account the regulatory framework. Specifically, the legal restrictions applicable to the simulator are specified.

3.4.1 Restricciones Legales

In the real BOINC system, users must be registered, and Berkeley Open Infrastructure for Network Computing (BOINC) databases handle confidential information from users, so it is necessary to ensure that third parties can not access that information. One solution is to encrypt the information transmitted following some cryptographic protocol. In Spain, this requirement is specified in the article 104 of the RD 1720/2007 [9], which deals with the Spanish Data Protection Law.

In contrast, the developed application does not use private data from users, and neither transmits any confidential information to third-parties, because it is just a simulator that does not even require Internet access.

On the other hand, it is crucial that our simulator be available as an open-source software. We want it to be such that anyone can redistribute the code or modify it by the terms of the GNU Lesser General Public License (LGPL) [10]. To do this, our simulator is available on the following website: <https://www.arcos.inf.uc3m.es/~combos/>.

Chapter 4

Diseño

This chapter provides a complete description of the developed simulator, including the internal architecture and the different software components. Complete BOINC Simulator (ComBoS) is a complete simulator of BOINC infrastructures that simulates the behavior of all componentes involved: projects, servers, network, scheduling, redundant computing, and volunteer nodes. In this chapter we describe all the simulator components (Section 4.1, *Componentes del Simulador*) and present the policies of the client scheduler (Section ??, ??).

4.1 Componentes del Simulador

4.1.1 Interfaz Gráfica

4.1.2 Core

4.1.3 Compilador

Chapter 5

Implementación y despliegue

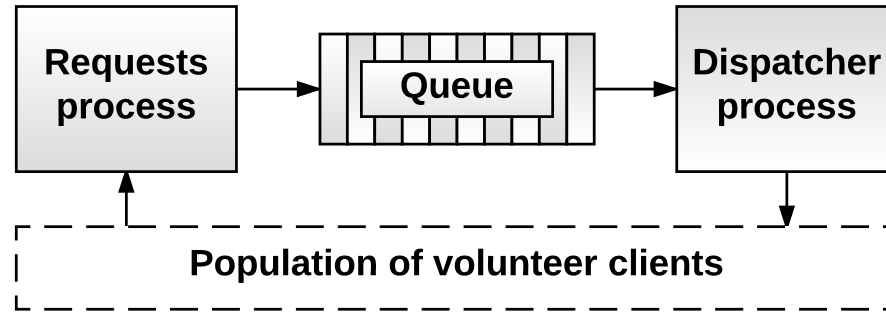
This chapter deals with the implementation and deployment of the software. Regarding the implementation of the system, the more complicated parts of the code are explained (Section 5.1, *Implementación*). On the other hand, we explain the steps required to deploy the final system (Section 5.2, *Deployment*).

5.1 Implementación

As we explained in Chapter 3, *Análisis*, we have implemented the simulator using the C programming language and the tools provided by SimGrid. The SimGrid core is responsible for planning the different processes, but the developer is the one that must use synchronization mechanisms to avoid race conditions. He have used several mutexes and condition variables in order to solve the problem of reading-writing in shared structures.

Furthermore, we have worked so that the project servers simulated in ComBoS have a realistic behavior. To do this, we have divided the functioning of each server (both scheduling and data servers) into two main processes: requests and dispatcher (see Figure 5-1).

The *requests* process is in charge of receiving all client requests through the corresponding mailbox. It receives messages asynchronously; that is, the process does not wait to finish receiving a message from a client in order to start receiving the next one. Each time a request is received, it is inserted into a queue that is shared with the *dispatcher* process. The dispatcher process is responsible for dealing with requests and answering to the volunteer clients if necessary. Response messages are sent asynchronously as well.

Figure 5-1: *Server main processes.*

On the other hand, each client is implemented with at least three different processes: the client main process (Pseudocode 5.1), which updates the client parameters every scheduling interval; the work fetch process (Pseudocode 5.2), which selects the project to ask for work; and the execution processes, one per attached project, that execute the tasks. We have not included the pseudocode of the execution process because it only dequeues tasks and executes them. Our simulator is complemented with the most important features of the real scheduler (deadline scheduling, long term debt, fair sharing and exponential back-off) as explained in Section ??, ?? (Chapter 4, *Diseño*).

Pseudocode 5.1 Client main process

```

1: function CLIENT_MAIN( )
2:   while time < max_time do
3:     increase wall_cpu_time to the running project
4:     UPDATE_DEBT
5:     UPDATE_DEADLINE_MISSED
6:     CPU_SCHEDULING
7:     SIGNAL Work fetch process
8:     WAIT scheduling_interval
9:   end while
10:  Return
11: end function
  
```

Pseudocode 5.2 Work fetch process

```

1: function WORK_FETCH( )
2:   project = null
3:   while time < max_time do
4:     for each project p in projects do
5:       if p meets the requirements then
6:         project = p
7:       end if
8:     end for
9:     if project and not deadlines_missed then
10:      ASK_FOR_WORK(project)
11:    end if
12:    WAIT work_fetch_period
13:  end while
14:  SIGNAL Client main process
15:  Return
16: end function

```

5.2 Deployment

This section presents the deployment of the system. The technical specifications recommended for the final user to obtain the best experience from the application are:

- **Operating System:** Ubuntu 14.04.4 LTS (Linux distribution) or higher.
- **Processor:** Intel(R) Core(TM) i7 CPU 920 @2.67GHz or higher.
- **RAM:** 8 GB or higher.
- **Storage:** 1 GB of free space in the Hard Disk Drive.
- **Network:** Internet connection is not required.
- **Software:** The following software must be installed in order to run the application:
 1. GCC (GNU Compiler) 5.1 or higher.
 2. SimGrid toolkit 3.10 or higher.

To make life easier for the end user, we have organized the application files in the simplest way possible. Figure 5-2 shows the initial structure of the application files.

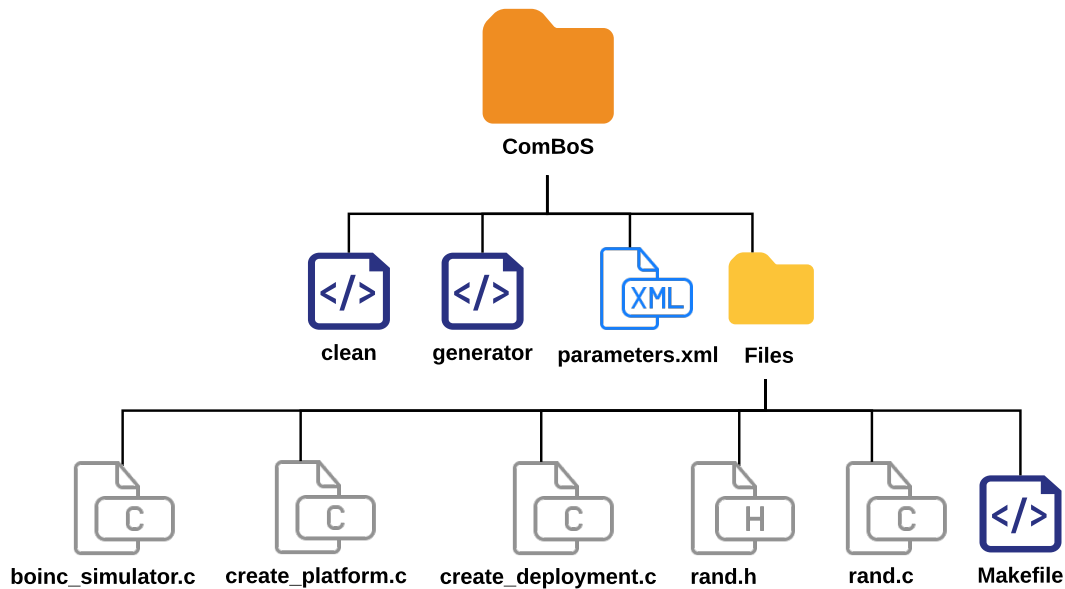


Figure 5-2: *Initial folder structure.*

The files located inside the ComBoS main folder are detailed below:

- **clean:** it is a script that removes the files created by the generator script.
- **generator:** it is a script that generates all the files needed for the simulation based on the parameters specified in the parameters.xml file. The files created by this script are:
 - **execute:** it is a script that executes the simulation (runs the file boinc_simulator).
 - **Files/create_platform:** it is the executable file that results from compiling the create_platform.c file.
 - **Files/create_deployment:** it is the executable file that results from compiling the create_deployment.c file.
 - **Files/platform.xml:** platform file created by create_platform.
 - **Files/deployment.xml:** deployment file created by create_deployment.
 - **Files/boinc_simulator:** it is the executable file that results from compiling the boinc_simulator.c and rand.c files.

- **parameters.xml:** to create a simulation, ComBoS requires the specification of all the parameters needed in an XML file, such as the simulation time in hours. All other parameters required by the XML file are detailed in Tables ?? and ?? (presented in Chapter 4, *Diseño*)
- **Files:** folder that includes:
 - **boinc_simulator.c:** simulator main source code.
 - **create_platform.c:** source code that contains the generation of the platform file.
 - **create_deployment.c:** source code that contains the generation of the deployment file.
 - **rand.h:** header file for random functions.
 - **rand.c:** source code that contains the random functions.
 - **Makefile:** script that compiles and links the code files.

The Appendix A presents a complete user manual of the simulator. It includes a tutorial for the installation of the SimGrid toolkit, and a number of practical and educational examples to learn how to perform simulations. In a basic way, in order to deploy the application, the user only needs to follow the following steps:

- Download the main folder of the ComBoS application (of which the structure is presented in Figure 5-2).
- Indicate the simulation parameters in the parameters XML file. This file must include all the parameters specified in Tables ?? and ?? (presented in Chapter 4, *Diseño*).
- Generate all the simulation files required, by just running the generator script.
- Run the execution script.

Chapter 6

Verificación, validación y evaluación

This chapter details the verification, validation and evaluation of the project. First, we present the verification and validation of the simulator (Section 6.1, *Verificación y validación*), and we detail a series of tests that allowed us to verify that we had met all the requirements set in Chapter 3 (*Análisis*). After this, we show the validation of the outputs of the simulations, demonstrating that the simulator performs accurate and realistic simulations. We also display a study of the performance of the simulator (Section 6.2, *Performance Study*), in which we show that ComBoS is efficient and scalable. Finally, we present several case studies of the simulator usage (Section 6.3, *Case Studies*), with the corresponding analysis and evaluation of the results.

We have used the `drand48` Linux functions [11] as random number generator in our simulations. These functions generate pseudo-random numbers using the linear congruential algorithm and 48-bit integer arithmetic. Each simulation result presented in this chapter is based on the average of 20 runs. For a 95% interval, the error is less than $\pm 3\%$ for all values.

6.1 Verificación y validación

The main objective of this section is to verify that all the requirements set out in Chapter 3 (*Análisis*) have been fulfilled. In addition, we validate the results provided by ComBoS, comparing them to the results of SimBOINC and to the statistical results of the official BOINC webpage.

In software engineering, verification and validation are the processes of checking that a software system meets specifications and that it fulfills its intended purpose. As explained in Chapter 3 (*Análisis*), the customer initially sets the requirements desired for the final product

(user requirements). From there, analysts specify software requirements (functional and non-functional requirements). In order to verify that the project requirements are met, verification and validation processes are needed (see Figure 6-1).

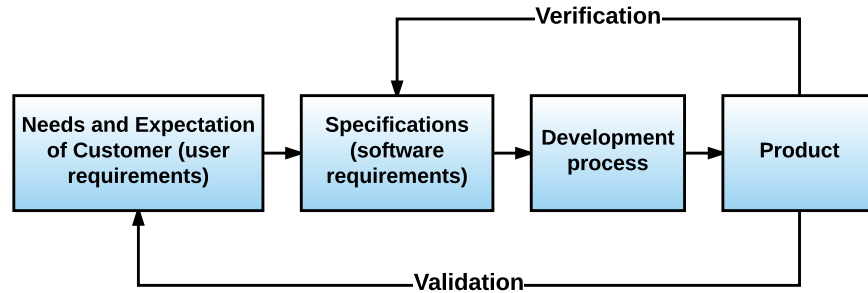


Figure 6-1: *Software verification and validation.*

Software verification is the process of evaluating work-products (not the actual final product) of a development phase to determine whether they meet the specified requirements for that phase (the software requirements). *Software validation* is the process of evaluating the final product at the end of the development process to determine whether it satisfies the requirements specified by the user at the beginning of the project [12].

6.1.1 Pruebas de verificación

In order to perform the verification tests, we have followed a dynamic process during the development phase of the software. With these tests we wanted to answer the question: “Are we building the product right?”. Table 6.1 provides the template used for the verification tests. Note that the ID format is VET-XX, where XX indicates the verification test number.

ID	Test ID.
Name	Test name.
Requirements	Software requirements fulfilled with this test.
Description	Test description.
Preconditions	Predicates that must always be true before performing the test.
Procedure	A fixed, step-by-step sequence of activities performed by the test.
Postconditions	Predicates that must always be true just after performing the test.
Evaluation	<i>Passed or Failed.</i>

Table 6.1: *Template for verification tests.*

Then, we specify the verification tests.

ID	VET-01
Name	Platform.
Requirements	SR-NF-PL01, SR-NF-PL02, SR-NF-PL03, SR-NF-UI02.
Description	Verify that the software can be used on the platform and is developed with the tools specified in the requirements.
Preconditions	<ol style="list-style-type: none"> 1. Use a machine with Ubuntu 14.04 operating system. 2. GCC (GNU Compiler) 5.1 or higher must be installed on the machine. 3. The user must be located in the main directory of the ComBoS application.
Procedure	<ol style="list-style-type: none"> 1. Check the code of the simulator source files (all these files are inside the /Files folder). 2. Run the generator script with the default parameters to create the simulation files. 3. Run the simulation.
Postconditions	<ol style="list-style-type: none"> 1. All source files must be written in C programming language. 2. The implementation, setup and control of the simulations must be carried out using the MSG API of the SimGrid toolkit. 3. Simulations run while a progress bar indicates the percentage of execution. 4. The simulator must successfully finish its execution in the specified operating system.
Evaluation	Passed

Table 6.2: *Verification test VET-01.*

ID	VET-02
Name	Realistic BOINC elements in simulations.
Requirements	SR-F-F06, SR-NF-UI01, SR-NF-UI02.
Description	Verify that the simulator allows to simulate all the BOINC actual elements.
Preconditions	<ol style="list-style-type: none"> 1. The user must be located in the main directory of the ComBoS application.
Procedure	<ol style="list-style-type: none"> 1. Specify the following elements in the simulation parameters: tasks, volunteer hosts, servers, data servers, networks, and hosts availability. 2. Run the generator script to create the simulation files. 3. Run the simulation.
Postconditions	<ol style="list-style-type: none"> 1. Simulations run while a progress bar indicates the percentage of execution. 2. The simulator must successfully finish its execution.
Evaluation	Passed

Table 6.3: *Verification test VET-02.*

ID	VET-03
Name	Statistics of BOINC projects.
Requirements	SR-F-F02, SR-NF-UI01, SR-NF-UI02.
Description	Verify that the outputs of the simulator are the same as those published by BOINCstats [7]. The outputs are: credits, hosts, active hosts, and FLOPS.
Preconditions	1. The user must be located in the main directory of the ComBoS application.
Procedure	1. Specify the simulation parameters. 2. Run the generator script to create the simulation files. 3. Run the simulation.
Postconditions	1. Simulations run while a progress bar indicates the percentage of execution. 2. The simulator must successfully finish its execution. 3. The outputs of the simulator contain at least: credits, hosts, active hosts, and FLOPS (The same as those published by BOINCstats [7]).
Evaluation	Passed

Table 6.4: *Verification test VET-03.*

ID	VET-04
Name	Multiple BOINC projects simultaneously.
Requirements	SR-F-F04, SR-NF-UI01, SR-NF-UI02.
Description	Verify that the simulator allows multiple project simulations simultaneously.
Preconditions	1. The user must be located in the main directory of the ComBoS application.
Procedure	1. Specify the simulation parameters of three different projects (for example, the SETI@home, Einstein@home, and LHC@home projects). 2. Run the generator script to create the simulation files. 3. Run the simulation.
Postconditions	1. Simulations run while a progress bar indicates the percentage of execution. 2. The simulator must successfully finish its execution.
Evaluation	Passed

Table 6.5: *Verification test VET-04.*

ID	VET-05
Name	BOINC client scheduler.
Requirements	SR-F-F05, SR-NF-UI01, SR-NF-UI02.
Description	Verify that the client scheduler implemented produces the same results as the actual BOINC scheduler.
Preconditions	1. The user must be located in the main directory of the ComBoS application.
Procedure	1. Specify the client side simulation parameters of three different projects: SETI@home, Einstein@home, and LHC@home. 2. Run the generator script to create the simulation files. 3. Run the simulation.
Postconditions	1. Simulations run while a progress bar indicates the percentage of execution. 2. The simulator must successfully finish its execution. 3. The outputs of the simulation are the same as the real BOINC client scheduler (it is detailed in 6.1.3, <i>Validation of the Client Scheduler</i>).
Evaluation	Passed

Table 6.6: *Verification test VET-05.*

ID	VET-06
Name	Accurate simulations of BOINC projects.
Requirements	SR-F-F01, SR-F-F03, SR-NF-UI01, SR-NF-UI02.
Description	Verify that the outputs of the simulator for existing projects (SETI@home, Einstein@home, and LHC@home) should be almost identical to those published in BOINCstats [7].
Preconditions	1. The user must be located in the main directory of the ComBoS application.
Procedure	1. Specify the simulation parameters of three different projects: SETI@home, Einstein@home, and LHC@home. 2. Run the generator script to create the simulation files. 3. Run the simulation.
Postconditions	1. Simulations run while a progress bar indicates the percentage of execution. 2. The simulator must successfully finish its execution. 3. The outputs of the simulation are the same as the actual BOINC projects, in terms of FLOPS and credit (it is detailed in 6.1.4, <i>Validation of Whole Simulator</i>).
Evaluation	Passed

Table 6.7: *Verification test VET-06.*

ID	VET-07
Name	Large simulations.
Requirements	SR-NF-S01, SR-NF-UI01, SR-NF-UI02.
Description	Verify the application is able to perform simulations with more than 100,000 hosts in a machine with at least 8 GB of RAM.
Preconditions	<ol style="list-style-type: none"> 1. Use a machine with at least 8GB or RAM. 2. The user must be located in the main directory of the ComBoS application.
Procedure	<ol style="list-style-type: none"> 1. Specify the simulation parameters with more than 100,000 hosts. 2. Run the generator script to create the simulation files. 3. Run the simulation.
Postconditions	<ol style="list-style-type: none"> 1. Simulations run while a progress bar indicates the percentage of execution. 2. The simulator must successfully finish its execution.
Evaluation	Passed

Table 6.8: *Verification test VET-07.*

ID	VET-08
Name	Execution time.
Requirements	SR-NF-P01, SR-NF-UI01, SR-NF-UI02.
Description	Check that simulations follow a linear execution time.
Preconditions	<ol style="list-style-type: none"> 1. The user must be located in the main directory of the ComBoS application.
Procedure	<ol style="list-style-type: none"> 1. Specify the simulation parameters with different workloads. 2. Run the generator script to create the simulation files. 3. Run the simulation. 4. Go to 2 specifying different simulation parameters.
Postconditions	<ol style="list-style-type: none"> 1. Simulations run while a progress bar indicates the percentage of execution. 2. The simulator must successfully finish its execution. 3. Check that executions follow a linear execution time when increasing the workload (it is detailed in 6.2, <i>Performance Study</i>).
Evaluation	Passed

Table 6.9: *Verification test VET-08.*

The verification test traceability matrix (Table 6.10) determines that all the software requirements have been verified during the development phase of the project.

Requirements	VET-01	VET-02	VET-03	VET-04	VET-05	VET-06	VET-07	VET-08
SR-F-F01						✓		
SR-F-F02			✓					
SR-F-F03						✓		
SR-F-F04				✓				
SR-F-F05					✓			
SR-F-F06		✓						
SR-NF-PL01	✓							
SR-NF-PL02	✓							
SR-NF-PL03	✓							
SR-NF-S01							✓	
SR-NF-P01								✓
SR-NF-UI01		✓	✓	✓	✓	✓	✓	✓
SR-NF-UI02	✓	✓	✓	✓	✓	✓	✓	✓

Table 6.10: *Verification test traceability matrix.*

6.1.2 Validation Tests

To perform the validation tests, we have checked the final software, comparing it with the user needs specified in Chapter 3 (*Análisis*). With these tests we want to answer the question: “Have we built the right product?”. Table 6.11 provides the template used for the validation tests. Note that the ID format is VAT-XX, where XX indicates the validation test number.

ID	Test ID.
Name	Test name.
Requirements	User requirements fulfilled with this test.
Verification tests	Verification tests that help us to validate this test.
Description	Test description.
Preconditions	Predicates that must always be true before performing the test.
Procedure	A fixed, step-by-step sequence of activities performed by the test.
Postconditions	Predicates that must always be true just after performing the test.
Evaluation	<i>Passed or Failed.</i>

Table 6.11: *Template for validation tests.*

Then, we specify the validation tests.

ID	VAT-01
Name	BOINC projects simulation.
Requirements	UR-C01.
Verification tests	VET-03, VET-06.
Description	Validate that the simulator is able to simulate the behavior of BOINC projects.
Preconditions	1. The user must be located in the main directory of the ComBoS application.
Procedure	<ol style="list-style-type: none"> 1. Specify the simulation parameters of three different BOINC projects: SETI@home, Einstein@home, and LHC@home. 2. Run the generator script to create the simulation files. 3. Run the simulation.
Postconditions	<ol style="list-style-type: none"> 1. The simulator must successfully finish its execution. 2. The outputs of the simulation are the same as the actual BOINC projects, in terms of FLOPS and credit (it is detailed in 6.1.4, <i>Validation of Whole Simulator</i>).
Evaluation	Passed.

Table 6.12: *Validation test VAT-01.*

ID	VAT-02
Name	Client scheduling.
Requirements	UR-C02.
Verification tests	VET-05.
Description	Validate that the client scheduler implemented produces the same results as the actual BOINC scheduler.
Preconditions	1. The user must be located in the main directory of the ComBoS application.
Procedure	<ol style="list-style-type: none"> 1. Specify the client side simulation parameters of three different projects: SETI@home, Einstein@home, and LHC@home. 2. Run the generator script to create the simulation files. 3. Run the simulation.
Postconditions	<ol style="list-style-type: none"> 1. The simulator must successfully finish its execution. 2. The outputs of the simulation are the same as the real BOINC client scheduler (it is detailed in 6.1.3, <i>Validation of the Client Scheduler</i>).
Evaluation	Passed.

Table 6.13: *Validation test VAT-02.*

ID	VAT-03
Name	Simulation components.
Requirements	UR-C03.
Verification tests	VET-02.
Description	Validate that the simulations cover all the elements of the BOINC infrastructure.
Preconditions	1. The user must be located in the main directory of the ComBoS application.
Procedure	1. Specify the following elements in the simulation parameters: tasks, volunteer hosts, servers, data servers, networks, and hosts availability. 2. Run the generator script to create the simulation files. 3. Run the simulation.
Postconditions	1. The simulator must successfully finish its execution.
Evaluation	Passed.

Table 6.14: *Validation test VAT-03.*

ID	VAT-04
Name	Platform.
Requirements	UR-R01, UR-R02.
Verification tests	VET-01.
Description	Validate that the software can be used on the platform and is developed with the tools specified in the requirements.
Preconditions	1. Use a machine with a Linux operating system. 2. The user must be located in the main directory of the ComBoS application.
Procedure	1. Check the code of the simulator source files (all these files are inside the /Files folder). 2. Run the generator script with the default parameters to create the simulation files. 3. Run the simulation.
Postconditions	1. The simulator must successfully finish its execution. 2. The implementation, setup and control of the simulations must be carried out using the MSG API of the SimGrid toolkit.
Evaluation	Passed.

Table 6.15: *Validation test VAT-04.*

ID	VAT-05
Name	Scalability.
Requirements	UR-R03.
Verification tests	VET-07.
Description	Validate that the application is able to perform large simulations.
Preconditions	1. The user must be located in the main directory of the ComBoS application.
Procedure	1. Specify the simulation parameters with more than 100,000 hosts. 2. Run the generator script to create the simulation files. 3. Run the simulation.
Postconditions	1. The simulator must successfully finish its execution.
Evaluation	Passed.

Table 6.16: *Validation test VAT-05.*

The validation test traceability matrix (Table 6.17) determines that all the user needs have been validated in the final product.

Requirements	VAT-01	VAT-02	VAT-03	VAT-04	VAT-05
UR-C01	✓				
UR-C02		✓			
UR-C03			✓		
UR-R01				✓	
UR-R02				✓	
UR-R03					✓

Table 6.17: *Validation test traceability matrix.*

6.1.3 Validation of the Client Scheduler

To validate the client scheduler of ComBoS, we have compared the results of different executions of the simulator with the equivalent SimBOINC simulations. Of course, as we only want to validate the client scheduler (individually), we have simulated scenarios with no delay caused by network or servers.

All scenarios considered are based on a single client host with three associated projects (Einstein@home, SETI@home and LHC@home). Through the different tests we have varied the priorities of the projects and the time of each simulation. When using hosts with the same power, our goal is to compare the number of tasks executed in each simulator.

As explained in Section ??, ?? (Chapter 2, *Estado del arte*), SimBOINC simulates the BOINC client scheduler and its simulations are highly accurate, because it uses almost exactly the BOINC client's CPU scheduler source code. Tables 6.18, 6.19 and 6.20 show different test cases:

- Table 6.18 presents the number of tasks executed by a client host of $1.4 \cdot 10^9$ FLOPS on simulations of 100, 500, 1,000, 5,000, and 10,000 hours. The priorities of the three projects are the same, so that each project uses the same runtime (33% CPU). The results of ComBoS and SimBOINC are almost identical.

Time in hours	<i>SimBOINC</i>			<i>ComBoS</i>		
	Einstein@home (33%)	SETI@home (33%)	LHC@home (33%)	Einstein@home (33%)	SETI@home (33%)	LHC@home (33%)
100	1	21	33	1	22	28
500	7	108	166	7	112	163
1,000	14	220	331	13	223	333
5,000	70	1,103	1,652	70	1,106	1,659
10,000	139	2,214	3,319	139	2,221	3,331

Table 6.18: *Executed tasks (three projects running on a single host of 1.4 GigaFLOPS).*

- Table 6.19 proposes a case similar to the previous test. In this case, the host has a power of $5.5 \cdot 10^9$ FLOPS and the priorities of the projects differ. The tasks of the LHC@home project consume 50% of CPU usage, while the tasks of the Einstein@home and SETI@home projects consume 25% of the CPU usage each. As in the previous case, the number of tasks executed in ComBoS is practically the same as in the case of SimBOINC.

Time in hours	<i>SimBOINC</i>			<i>ComBoS</i>		
	Einstein@home (25%)	SETI@home (25%)	LHC@home (50%)	Einstein@home (25%)	SETI@home (25%)	LHC@home (50%)
100	4	67	181	4	64	182
500	21	332	975	21	333	975
1,000	42	662	1,955	40	662	1,981
5,000	208	3,297	9,831	206	3,297	9,889
10,000	416	6,581	19,637	413	6,593	19,784

Table 6.19: Executed tasks (three projects running on a single host of 5.5 GigaFLOPS).

- Table 6.20 includes three different test cases. In each test case, a host of FLOPS $5.5 \cdot 10^9$ runs a unique project (100% of the CPU time). In the first case, the host performs tasks of Einstein@home project and the results are exactly the same in both simulators. In the case of SETI@home and LHC@home projects the results vary minimally.

Time in hours	<i>Einstein@home</i> (100%)		<i>SETI@home</i> (100%)		<i>LHC@home</i> (100%)	
	SimBOINC	ComBoS	SimBOINC	ComBoS	SimBOINC	ComBoS
100	16	16	263	263	395	394
500	82	82	1,318	1,319	1,978	1,972
1,000	164	164	2,637	2,639	3,956	3,945
5,000	824	824	13,177	13,195	19,780	19,728
10,000	1,649	1,649	26,315	26,390	39,473	39,457

Table 6.20: Executed tasks (single project running on a single host of 5.5 GigaFLOPS).

If we consider only the client scheduler, ComBoS results match those of SimBOINC, demonstrating the proper functioning of the simulator in this regard.

6.1.4 Validation of Whole Simulator

To validate the complete simulator, we have relied on data from the BOINCstats website [7], which provides official statistical results of BOINC projects. In this section, we analyze the behavior of ComBoS considering the simulation results of the SETI@home, Einstein@home and LHC@home projects.

We have used the CPU power traces of the client hosts that make up the VN of each project [13, 14, 15]. We have not used any other traces. In order to model the availability and unavail-

ability of the hosts, we used the results obtained in [16]. This research analyzed about 230,000 hosts' availability traces obtained from the SETI@home project. According to this paper, 21% of the hosts exhibit truly random availability intervals, and it also measured the goodness of fit of the resulting distributions using standard probability-probability (PP) plots. For availability, the authors saw that in most cases the Weibull distribution is a good fit. For unavailability, the distribution that offers the best fit is the log-normal. The parameters used for the Weibull distribution are $shape = 0.393$ and $scale = 2.964$. For the log-normal, the parameters obtained and used in ComBoS are a distribution with mean $\mu = -0.586$ and standard deviation $\sigma = 2.844$. All these parameters were obtained from [16] too. For the network parameters, we have used the bandwidth and latency values of current ADSL networks, and 10 Gbps for the network backbone. SimGrid's models allow us to adjust this network values. We have obtained all the other parameters of the simulations from the official websites of the SETI@home, Einstein@home, and LHC@home projects.

Project	Total hosts	Active hosts	BOINCstats		ComBoS	
			GigaFLOPS	Credit/day	GigaFLOPS	Credit/day
SETI@home	3,970,427	175,220	864,711	171,785,234	865,001	168,057,478
Einstein@home	1,496,566	68,338	1,044,515	208,902,921	1,028,172	205,634,486
LHC@home	356,942	15,814	7,521	1,504,214	7,392	1,393,931

Table 6.21: *Validation of the whole simulator.*

Table 6.21 compares the actual results of the SETI@home, Einstein@home and LHC@home projects with those obtained with ComBoS in terms of GigaFLOPS and credits. The error obtained is 2.2% for credit/day and 0.03% for GigaFLOPS compared to the SETI@home project; 1.6% for credit/day and for GigaFLOPS compared to the Einstein@home project; and 7.3% for credit/day and 1.7% for GigaFLOPS compared to the LHC@home project. We consider that these results allow us to validate the whole simulator.

6.2 Performance Study

In this section we analyze the performance of the simulator in terms of memory usage and execution time. All measurements were made on a computer with 32 GB of RAM and 8 Intel Core i7 processors running at 2.67 Ghz each. The server runs the Linux 3.13.0-85-generic kernel. It runs the 3.10 version of the SimGrid toolkit. In spite of the computer has eight cores, each simulation was performed individually in a single core.

Figure 6-2a shows the memory usage of the simulator and Figure 6-2b shows the execution time by increasing the number of client hosts in each simulation. Note that the tests have been carried out up to 1 million hosts, the same number of active hosts of all BOINC projects together. Figure 6-2a shows a linear ($O(n)$) memory footprint. Figure 6-2b shows the execution time of the simulator for four different simulation times: 1 day, 2 days, 3 days and 4 days. Both metrics demonstrate that the simulator is highly scalable. This has been possible due to the high performance [17] of the SimGrid toolkit.

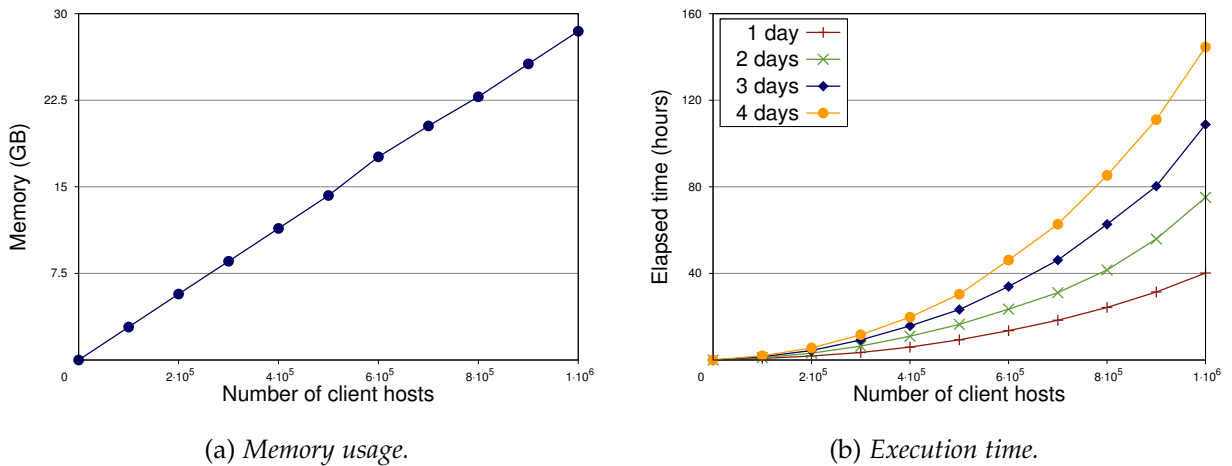


Figure 6-2: Performance study.

6.3 Case Studies

6.3.1 Combined Results

Chapter 7

Planificación y presupuesto

This chapter presents a detailed planning of the project (Section 7.1, *Planificación*). Then, we explain the project costs (Section 7.2, *Presupuesto*). At the end of the chapter, we comment on the socio-economic environment of the project (Section 7.3, *Entorno Socio-Económico*).

7.1 Planificación

This section includes the complete project planning. First, we describe the software development methodology used. After that, we detail the time duration of each phase of the project, collecting all times in a Gantt chart.

7.1.1 Justificación de la Metodología

Due to its characteristics, we have divided our project into three iterations:

- **Basic functionality:** the first iteration has been to achieve the simulation of a simple distributed computing system. The aim of this phase has been to simulate client machines that exchange messages with a server through the a network.
- **Client side:** this phase has been to incorporate all the necessary functionality on the client side (described in Chapter 4, *Diseño*).
- **Server side:** this phase has been to incorporate all the necessary functionality on the server side (described in Chapter 4, *Diseño*).

It was necessary to have an iterative methodology used to develop each of the phases independently to join all together in the last stage and obtain the final product. For this purpose, we have analyzed three different software development methodologies: Software prototyping [18], the Waterfall model [19] and the Spiral model [20]. Software prototyping did not fit well because it requires building a prototype of the software in a short time. The Waterfall model is a sequential design process, used in software development processes, in which progress is seen as flowing steadily downwards (like a waterfall) through different phases. The problem with this methodology is that it does not allow iterations within the software development. Finally, the Spiral model allowed fragmenting the project into different iterations. The model combines the strengths of the other two models (simplicity and flexibility), and uses an iterative process. Although this model is slower than the other two, it allowed us to apply different iterations so we decided to apply it to the whole process.

7.1.2 Ciclo de Vida

The life cycle development process of the project has followed the Spiral lifecycle model [20]. Figure 7-1 shows the Spiral model using a scheme.

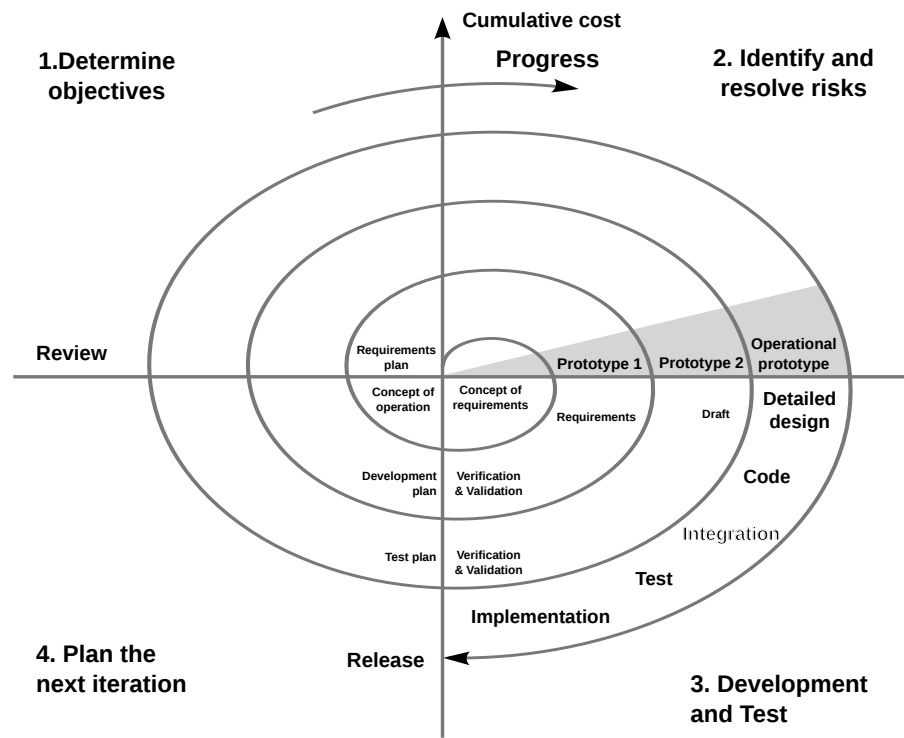


Figure 7-1: *Spiral model (Boehm, 2000).*

The Spiral model has four phases, which are repeated during the different iterations of the model. These phases are:

- **Planning** (Determine objectives in Figure 7-1): the user requirements are gathered, a feasibility study of the system is performed, and the iteration objectives are determined.
- **Analysis** (Identify and resolve risks in Figure 7-1): a full analysis of requirements is done and the potential risks are identified. This phase ends with a basic design.
- **Development and Test**: Code implementation is done. Test cases and test results are performed.
- **Evaluation** (Plan the next iteration in Figure 7-1): Customers evaluate the software and provide their feedback. In this case, the student tries to get the supervisor's approval. This is the *critical task* of the life cycle, since we can only move on to the next iteration of the Spiral lifecycle model if this task is approved.

Each phase starts with a design goal and ends with the customer (the supervisor) reviewing the progress so far. As previously explained, we have divided the software development into three iterations: basic functionality, client side, and server side. In the last iteration, the complete software must undergo extensive testing in order to validate the simulator.

7.1.3 Tiempo Estimado

The Gantt chart (Figure 7-2) shows all the tasks carried out during the project development. This project has been developed within a Collaboration in University Departments Scholarship [21], funded by the Spanish Ministry of Education, Culture, and Sport. The project began on November 2st, 2015, and ended on June 22, 2016, making a total of almost eight months of work. During this time, I have worked from Monday to Friday, four hours a day.

The Gantt chart shows all the tasks performed in each iteration of the spiral lifecycle model. Recall that the three iterations were: Basic functionality, Client side and Server side. In addition to the tasks (phases) mentioned above (Planning, Analysis, Development and Test, and Evaluation), we have included the Documentation task at the end of each iteration. The Documentation task has consisted mainly in drafting this bachelor thesis.

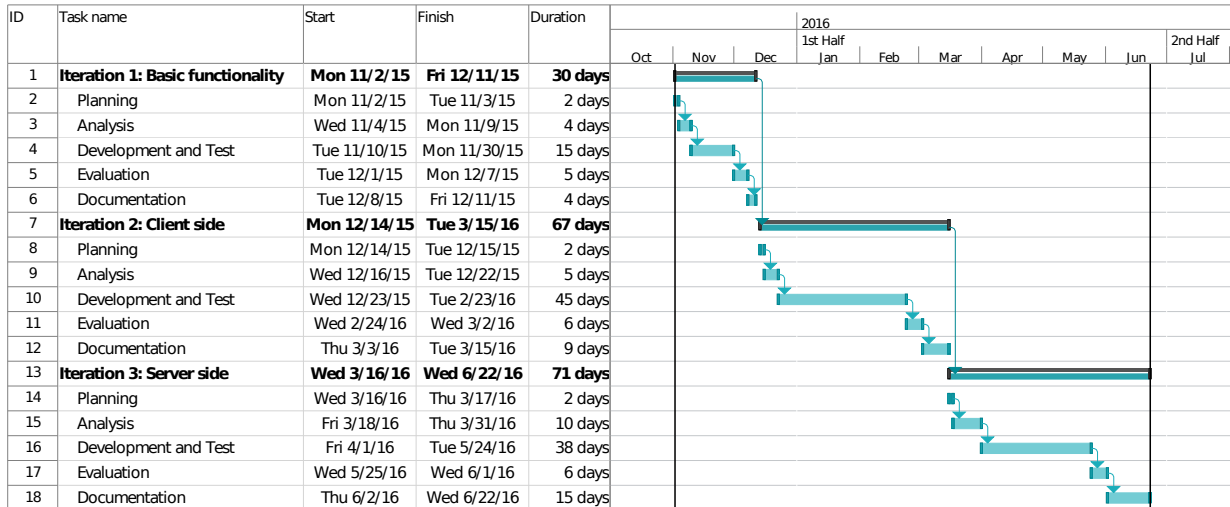


Figure 7-2: Gantt chart.

7.2 Presupuesto

This section details the overall project budget. On the one hand, we present the project costs and, on the other hand, we disclose the offer presented to the customer.

7.2.1 Coste del Proyecto

Table 7.1 summarizes the main features of the project including the total budget.

<i>Project Information</i>	
Title	A Complete Simulator for Volunteer Computing Environments
Author	Saúl Alonso Monsalve
Department	Computer Science and Engineering Department
Start date	2nd of November of 2015
End date	22nd of June of 2016
Duration	8 months
Indirect costs ratio	20 %
Total budget	30,526.49

Table 7.1: Project Information.

Then the total budget of the project is broken down below.

Costes Directos

In this part, the direct costs of the project are presented. Table 7.2 shows the direct costs caused by personnel costs, based on the planning presented in the previous section. The supervisor and the student have played the following roles:

- **Supervisor:** Project manager.
- **Student:** Analyst, Developer, Tester.

Category	Cost per hour (€)	Hours	Total (€)
Project manager	60	56	3,360
Analyst	35	188	6,580
Developer	35	316	11,060
Tester	25	112	2,800
Total			23,800.00

Table 7.2: *Human resources costs.*

Table 7.3 shows the direct costs caused by equipment acquisition and usage. The chargeable cost, C , is calculated using the following formula:

$$C = \frac{d \cdot c \cdot u}{D} \quad (7.1)$$

Where:

- **C:** Chargeable cost. It is equivalent to the depreciated value.
- **d:** Time the equipment has been used.
- **c:** Equipment cost.
- **u:** Project dedication. Percentage of time the equipment has been used.
- **D:** Equipment depreciation period.

Concept	Cost, c (€)	Dedication, u (%)	Dedication, d (months)	Depreciation, D (months)	Chargeable cost, C (€)
Desktop PC	799.99	100	8	36	177.78
Laptop	529.99	25	8	36	29.44
ARCOS Tucan	89,501.60	10	6	60	895.02
ARCOS Mirlo	2,469.99	70	6	60	172.90
Printer	399.24	5	3	60	1.00
Total					1,276.14

Table 7.3: *Equipment costs.*

Furthermore, the equipment presented in Table 7.3 is detailed below:

- **Desktop PC:** All in One - Asus Z220ICUK, 21.5", i5-6400T, 8GB, 1TB)
- **Laptop:** Toshiba L50D-C-19D, A10-8700P, 8GB RAM and 1TB.
- **ARCOS Tucan:** Cluster used by the research group ARCOS.
- **ARCOS Mirlo:** Server used by the research group ARCOS. 32GB RAM and eight i7 processors of 2.67GHz each.
- **Printer:** HP LaserJet Enterprise P3015.

Other direct costs are shown in Table 7.4. These costs consist of office material, a toner for the printer, and the monthly travel pass. Office material includes: pencils, pens, notebooks, paper, tipex, and markers.

Concept	Cost (€)
Office material	112.98
Toner (x1)	89.62
Monthly travel pass (x8)	160
Total	362.60

Table 7.4: *Other direct costs.*

Resumen de Costes

Table 7.5 shows the complete summary of the project costs. Indirect costs (20% of direct costs) consist of the electricity and water bills, telephone, Internet access, etc.

<i>Costs summary</i>	
Human resources	23,800.00
Equipment	1,276.14
Other direct costs	362.60
Indirect costs	5,087.75
<i>Total budget</i>	30,526.49

Table 7.5: *Costs summary.*

The total budget for this project amounts to **30,526.49 € (thirty thousand five hundred twenty-six euro and forty-nine cent)**.

7.2.2 Oferta de Proyecto Propuesta

Table 7.6 shows a detailed offer proposal. This offer includes the estimated risks (20%), the expected benefits (15%), and the Value Added Tax (Spanish Impuesto Sobre el Valor Añadido (IVA)), which corresponds to 21% [22]. After applying all theses concepts, the final amount for this project in case of sale to a third-party client is **50,973.14 € (fifty thousand nine hundred seventy-three euro and fourteen cent)**.

<i>Offer proposal</i>			
Concept	Increment (%)	Partial value (€)	Aggregated cost (€)
Project costs	-	30,526.49	30,526.49
Risk	20	6,105.30	36,631.79
Benefits	15	5,494.77	42,126.56
IVA	21	8,846.58	50,973.14
<i>Total</i>			50,973.14

Table 7.6: *Offer proposal.*

7.3 Entorno Socio-Económico

As commented in previous chapters, ComBoS can guide the design of BOINC projects. This means that BOINC project designers can perform accurate simulations using ComBoS before deploying the system. Thanks to this, designers can save money and resources, because they will know the performance of the system before deploying it. In addition, it can also save energy because designers will not need to perform tests using the original infrastructure, as they will only need to use ComBoS in order to analyze the functioning of different alternatives.

Moreover, BOINC operates as a platform for distributed applications in areas as diverse as mathematics, medicine, molecular biology, climatology, environmental science, and astrophysics. On the one hand, there are projects that help the scientific community, such as the SETI@home project [23], of which the purpose is to analyze radio signals, searching for signs of extraterrestrial intelligence; or the Citizen Science Grid project [24], which is dedicated to supporting a wide range of research and educational projects. On the other hand, there are projects dedicated to the environmental care, such as the Climateprediction.net project [25], which studies climate. Therefore, our simulator indirectly contributes to both science and the environment.

Chapter 8

Conclusiones y trabajos futuros

In this chapter we discuss the main contributions of our work. In addition, we present the conclusions of the work, revise the objectives set at the beginning of this document, and include some personal conclusions. Finally, we discuss future work.

8.1 Contribuciones

8.2 Conclusiones

8.3 Trabajos Futuros

Appendix A

User Manual

This appendix presents a detailed user manual of ComBoS. First we indicate the basic requirements to deploy the application and a detailed tutorial for the installation of SimGrid. Finally, we present an example of the simulator usage.

A.1 Basic Requirements

The technical specifications recommended for the final user to obtain the best experience from the application are:

- **Operating System:** Ubuntu 14.04.4 LTS (Linux distribution) or higher.
- **Processor:** Intel(R) Core(TM) i7 CPU 920 @2.67GHz or higher.
- **RAM:** 8 GB or higher.
- **Storage:** 1 GB of free space in the Hard Disk Drive.
- **Network:** Internet connection is not required.
- **Software:** The following software must be installed in order to run the application:
 1. GCC (GNU Compiler) 5.1 or higher.
 2. SimGrid toolkit 3.10 or higher.

A.2 SimGrid Installation

We will present a tutorial for the installation of the SimGrid toolkit (version 3.10). First, you have to download the official binary package from the *download page* (<http://simgrid.gforge.inria.fr/download.php>). In this case you will download the file *SimGrid-3.10.tar.gz*.

Then, you have to recompile the archive. This should be done in a few lines:

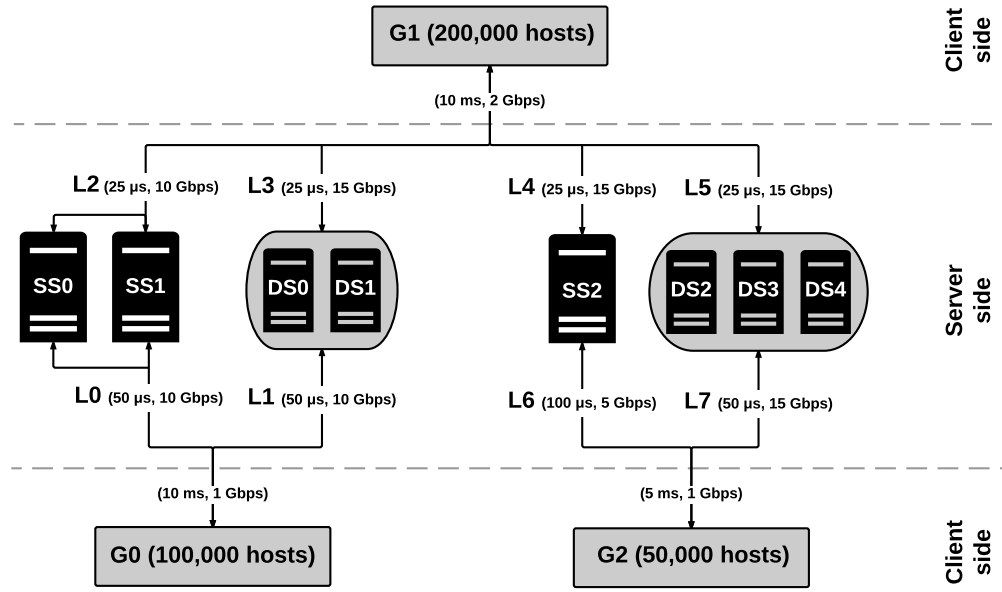
```
$ tar xf SimGrid-3.10.tar.gz
$ cd SimGrid-3.10
$ cmake -DCMAKE_INSTALL_PREFIX=/opt/simgrid $HOME
$ make
$ make install
```

After following these steps, you will have the SimGrid toolkit installed in your computer.

A.3 Usage Example

In order to use ComBoS, you must download the corresponding files from the following website: <https://www.arcos.inf.uc3m.es/~combos/>. After unzipping the downloaded file, the unzipped files will follow the folder structure presented in Figure 5-2 (Section 5.2, *Deployment* (Chapter 5, *Implementación y despliegue*)). To perform simulations using ComBoS, it is necessary to model the platform to be simulated. Once you know the environment to simulate, you must specify all simulation parameters in the parameters XML file.

Figure A-1 shows an example of a potential simulation that can be carried out by ComBoS. The figure shows a simplified platform with two BOINC projects and 350,000 clients. The first project is represented by two scheduling servers (SS0 and SS1) and two data servers (DS0 and DS1). The second project consists of a single scheduling server (SS2) and three data servers (DS2, DS3 and DS4). Clients are grouped into three sets. The first group (G0) consists of 100,000 hosts and has a route to the first project. The second group (G1), has 200,000 hosts and a route to both projects. The third group (G2) consists of 50,000 computers and has route to the second project. The rest of the figure shows the links among the elements of the environment (from L0 to L7). In each of the links, latency and bandwidth are indicated.

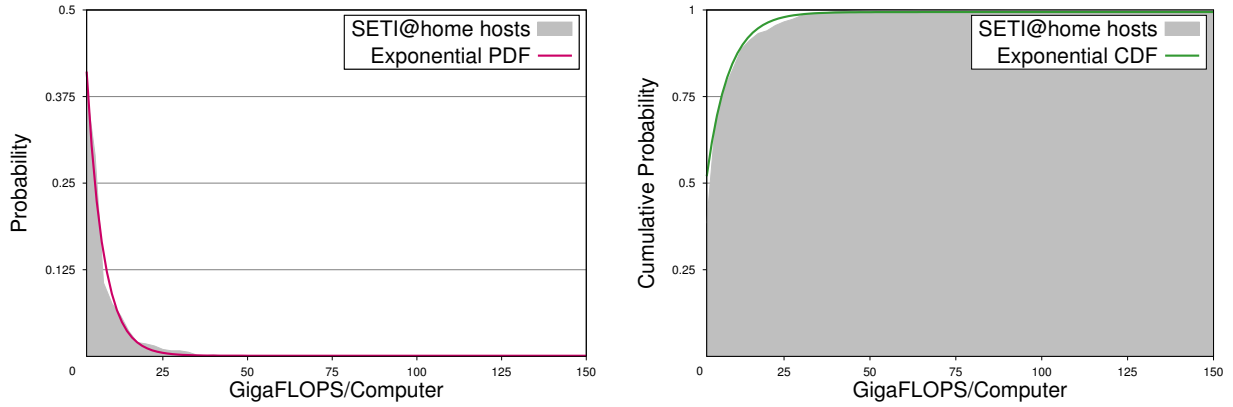
Figure A-1: *Simulator platform example.*

To create a simulation, ComBoS requires to specify all the parameters described in Tables ?? and ?? in the parameters.xml file (see Listing A.1). Users can define the power and availability of the volunteer hosts via either a traces file or distribution functions. For example, in the case of the SETI@home project, we have analyzed the 3,900,000 hosts that participate in this project. The CPU performance of the hosts can be modeled according to an exponential function, as shown Figure A-2, which has a mean of 5.871 GigaFLOPS per host.

Our software first processes the XML file, creating the necessary deployment and platform files for subsequent simulations. In ComBoS, all this is transparent to the user. The user only has to specify all the parameters of the simulation in the XML file (Listing A.1), and run the generator script using the following command:

```
$ ./generator
```

The above command generates the platform and deployment files. The platform file contemplates all the necessary elements in the simulation: hosts, clusters, links, etc. The deployment file indicates the processes that should be created during the simulation. In addition, the generator script also compiles all source files needed for the simulation and generates the executable file. Finally, to run the simulation you just need to run the execution script:



(a) *Probability density function of SETI@home hosts power.*

(b) *Cumulative distribution function of SETI@home hosts power.*

Figure A-2: CPU performance modeling for SETI@home hosts.

```
$ ./execute
```

The execution results are composed by multiple statistical results (see Listings A.2): the execution time, the memory usage of the simulator, the load of the scheduling and data servers, the total number of work requests received in the scheduling servers, the job statistics (number of jobs created, sent, received, analyzed, success, fail, too late, etc), the credit granted to the clients, the number of FLOPS, the average power of the volunteer nodes, and the percentage of time the volunteer nodes were available during the simulation.

```

1 <simulation_time>100</simulation_time>
2
3 <!-- Server side -->
4 <server_side>
5   <n_projects>2</n_projects>
6   <sproject>
7     <snumber>0</snumber>
8     <name>PROJECT1</name>
9     <nscheduling_servers>2</nscheduling_servers>
10    <ndata_servers>2</ndata_servers>
11    <server_pw>12000000000.0</server_pw>
12    <disk_bw>80000000</disk_bw>
13    <ifgl_percentage>100</ifgl_percentage>
14    <ifcd_percentage>100</ifcd_percentage>
15    <input_file_size>368640</input_file_size>
16    <task_fpop>7560000000000</task_fpop>
17    <output_file_size>65536</output_file_size>
18    <min_quorum>2</min_quorum>
19    <target_nresults>2</target_nresults>
20    <max_error_results>2</max_error_results>
21    <max_total_results>4</max_total_results>
22    <max_success_results>3</max_success_results>
23    <delay_bound>100000000</delay_bound>
24    <success_percentage>95</success_percentage>
25    <canonical_percentage>95</canonical_percentage>
26    <replication>2</replication>
27  </sproject>
28  <sproject>
29    <snumber>1</snumber>
30    <name>PROJECT2</name>
31    <nscheduling_servers>1</nscheduling_servers>
32    <ndata_servers>3</ndata_servers>
33    <server_pw>12000000000.0</server_pw>
34    <disk_bw>60000000</disk_bw>
35    <ifgl_percentage>100</ifgl_percentage>
36    <ifcd_percentage>100</ifcd_percentage>
37    <input_file_size>52428800</input_file_size>
38    <task_fpop>20800000000000</task_fpop>
39    <output_file_size>16777216</output_file_size>

```

```

40     <min_quorum>2</min_quorum>
41     <target_nresults>2</target_nresults>
42     <max_error_results>2</max_error_results>
43     <max_total_results>4</max_total_results>
44     <max_success_results>3</max_success_results>
45     <delay_bound>100000000</delay_bound>
46     <success_percentage>95</success_percentage>
47     <canonical_percentage>95</canonical_percentage>
48     <replication>2</replication>
49     <project/>
50 </server_side>
51
52 <!-- Client side -->
53 <client_side>
54     <n_groups>3</n_groups>
55     <group>
56         <n_clients>100000</n_clients>
57         <connection_interval>1</connection_interval>
58         <scheduling_interval>3600</connection_interval>
59         <gbw>1Gbps</gbw>
60         <glatency>10ms</glatency>
61         <traces_file>NULL</traces_file>
62         <max_speed>117.71</max_speed>
63         <min_speed>0.07</min_speed>
64         <pv_distri>5</pv_distri>
65         <pa_param>0.1734</pa_param>
66         <pb_param>-1</pb_param>
67         <av_distri>0</av_distri>
68         <aa_param>0.393</aa_param>
69         <ab_param>2.964</ab_param>
70         <nv_distri>2</nv_distri>
71         <na_param>2.844</na_param>
72         <nb_param>-0.586</nb_param>
73         <att_projs>1</att_projs>
74         <gproject>
75             <pnumber>0</pnumber>
76             <priority>1</priority>
77             <lsbw>10Gbps</lsbw>
78             <lslatency>50us</lslatency>

```

```

79     <ldbw>10Gbps</ldbw>
80     <ldlatency>50us</latency>
81 </gproject>
82 </group>
83 <group>
84     <n_clients>200000</n_clients>
85     <connection_interval>1</connection_interval>
86     <scheduling_interval>3600</connection_interval>
87     <gbw>2Gbps</gbw>
88     <glatency>10ms</glatency>
89     <traces_file>NULL</traces_file>
90     <max_speed>117.71</max_speed>
91     <min_speed>0.07</min_speed>
92     <pv_distri>5</pv_distri>
93     <pa_param>0.1734</pa_param>
94     <pb_param>-1</pb_param>
95     <av_distri>0</av_distri>
96     <aa_param>0.393</aa_param>
97     <ab_param>2.964</ab_param>
98     <nv_distri>2</nv_distri>
99     <na_param>2.844</na_param>
100    <nb_param>-0.586</nb_param>
101    <att_projs>2</att_projs>
102    <gproject>
103        <pnumber>0</pnumber>
104        <priority>1</priority>
105        <lsbw>10Gbps</lsbw>
106        <lslatency>25us</lslatency>
107        <ldbw>15Gbps</ldbw>
108        <ldlatency>25us</latency>
109    </gproject>
110    <gproject>
111        <pnumber>1</pnumber>
112        <priority>1</priority>
113        <lsbw>15Gbps</lsbw>
114        <lslatency>25us</lslatency>
115        <ldbw>15Gbps</ldbw>
116        <ldlatency>25us</latency>
117    </gproject>

```

```

118 </group>
119 <group>
120   <n_clients>50000</n_clients>
121   <connection_interval>1</connection_interval>
122   <scheduling_interval>3600</connection_interval>
123   <gbw>1Gbps</gbw>
124   <glatency>5ms</glatency>
125   <traces_file>NULL</traces_file>
126   <max_speed>117.71</max_speed>
127   <min_speed>0.07</min_speed>
128   <pv_distri>5</pv_distri>
129   <pa_param>0.1734</pa_param>
130   <pb_param>-1</pb_param>
131   <av_distri>0</av_distri>
132   <aa_param>0.393</aa_param>
133   <ab_param>2.964</ab_param>
134   <nv_distri>2</nv_distri>
135   <na_param>2.844</na_param>
136   <nb_param>-0.586</nb_param>
137   <att_projs>1</att_projs>
138   <gproject>
139     <pnumber>1</pnumber>
140     <priority>1</priority>
141     <lsbw>5Gbps</lsbw>
142     <lslatency>100us</lslatency>
143     <ldbw>15Gbps</ldbw>
144     <ldlatency>50us</latency>
145   </gproject>
146 </group>
147 </client_side>

```

Listing A.1: *parameters.xml* file filled with the parameters of the example.

```
1  Memory usage: 11,570,812 KB
2
3  Total number of clients: 350,000
4
5  ##### PROJECT1 #####
6
7  Simulation ends in 100 h (360,000 sec)
8
9  Scheduling server 0: Busy: 13.4%
10 Scheduling server 1: Busy: 13.4%
11 Data server 0: Busy: 12.2%
12 Data server 1: Busy: 12.2%
13
14 Number of clients: 300,000
15 Messages received: 32,227,795 (work requests received + results received)
16 Work requests received: 16,179,688
17 Results created: 16,179,689 (100.0%)
18 Results sent: 16,179,688 (100.0%)
19 Results received: 16,048,107 (99.2%)
20 Results analyzed: 16,048,107 (100.0%)
21 Results success: 15,245,637 (95.0%)
22 Results failed: 802,470 (5.0%)
23 Results too late: 0 (0.0%)
24 Results valid: 13,616,636 (84.8%)
25 Workunits total: 7,716,639
26 Workunits completed: 6,863,142 (88.9%)
27 Workunits not completed: 853,497 (11.1%)
28 Workunits valid: 6,808,318 (88.2%)
29 Workunits error: 54,824 (0.7%)
30 Throughput: 89.5 mens/s
31 Credit granted: 231,482,812 credits
32 FLOPS average: 285,949 GFLOPS
33
34 ##### PROJECT2 #####
35
36 Simulation ends in 100 h (360,000 sec)
37
38 Scheduling server 0: Busy: 1.7%
39 Data server 0: Busy: 100.0%
```

```

40 Data server 1: Busy: 100.0%
41 Data server 2: Busy: 100.0%
42
43 Number of clients: 250,000
44 Messages received: 2,070,120 (work requests received + results received)
45 Work requests received: 1,161,080
46 Results created: 1,161,081 (100.0%)
47 Results sent: 1,161,080 (100.0%)
48 Results received: 909,040 (78.3%)
49 Results analyzed: 909,040 (100.0%)
50 Results success: 863,710 (95.0%)
51 Results failed: 45,330 (5.0%)
52 Results too late: 0 (0.0%)
53 Results valid: 743,688 (81.8%)
54 Workunits total: 559,384
55 Workunits completed: 374,713 (67.0%)
56 Workunits not completed: 184,671 (33.0%)
57 Workunits valid: 371,844 (66.5%)
58 Workunits error: 2,869 (0.5%)
59 Throughput: 5.8 mens/s
60 Credit granted: 35,697,024 credits
61 FLOPS average: 42,968 GFLOPS
62
63 Group 0. Average speed: 6.704465 GFLOPS. Available: 62.1% Not available 37.9%
64 Group 1. Average speed: 5.455870 GFLOPS. Available: 55.3% Not available 44.7%
65 Group 2. Average speed: 6.110686 GFLOPS. Available: 57.0% Not available 43.0%
66
67 Clients. Average speed: 5.906157 GFLOPS. Available: 57.5% Not available 42.5%
68
69 Execution time:
70 0 days 7 hours 51 min 49 s

```

Listing A.2: *Simulation execution results.*

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