Italsim: A Knowledge-Based Simulation of a PCB Manufacturing Plant

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ABSTRACT

Italsim is a simulation system developed to model and simulate a printed circuit board (PCB) manufacturing plant. The primary contribution of the system is its display of the efficacy of the knowledge-based approach as applied to a real-world simulation problem. The system utilises the Integrated Modeling Package (IMP), a software package developed specifically for knowledge-based manufacturing applications, and runs on lisp workstations. An initial model has been completed, comprising 85 operations, 120 operators, and 165 distinct board routings. The model was developed by automatically extracting information from the data base of an existing tracking system, and a simulation may be executed by loading, as a starting state, a snapshot of a dynamic plant configuration. Italsim is currently in field test by the production staff at the PCB plant.

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INTRODUCTION

In April of 1987 Italtel, a communications company located in Settimo Milanese, Italy, and Carnegie (U.K.) Limited, an expert systems company located in Ascot, England, initiated the Italsim (Italtel Simulator) project. The goal of the Italsim project was to develop a knowledge-based simulation for a manufacturing plant which produces printed circuit boards (PCBs) for electronic switching equipment.

Previously, Italtel had engaged in a project to develop a PC-based simulation for the PCB plant. The requirements for the simulation defined by the production management were typical of such projects. It was believed that a simulation system would assist production in the short term by enabling the plant supervisors to experiment with hypothetical plant procedures without interfering with daily plant operation. Additionally, it was conjectured that foreseeing possible bottlenecks would aid in operator scheduling and dynamic replanning. In the long term, management hoped that the simulation would aid in the modification of plant setup and in the design of future plants. Unfortunately, the results of the PC-based simulation were disappointing. The simulation did not deliver on any of the requirements and, in addition, was inaccurate, difficult to use, and difficult to modify.

Because of the shortcomings of the PC-based approach, the Italsim project was initiated. Italsim utilises a knowledge-based approach. There are a number of potential advantages of such a strategy. First, model creation and modification may be simplified through the use of symbolic and knowledge-based models. Second, the use of specialised knowledge engineering hardware and software greatly reduces software development time. Finally, the use of the new techniques provided by knowledge-based technology supports the possibility for development of advanced simulation analysis and validation.

Of course, the use of this relatively new technology presented potential obstacles as well. Most existing knowledge-based simulation systems have been developed with research objectives, rather than practical goals, as their basis. Therefore, a record of proven success does not exist. Additionally, knowledge-based systems are typically slower and less efficient than conventional systems. We thus undertook the Italsim project with the intention of retaining the advantages of the knowledge-based approach while focusing on the development of a large, real-world application which would provide adequate efficiency for use by production personnel.

DESCRIPTION OF THE ITALTEL PCB DOMAIN

Printed circuit boards begin in the Italtel plant as "bare" boards. Throughout a series of operations, hundreds of components, from a set of fifty thousand component types, are inserted. The boards are then soldered and washed. When fully assembled, they undergo a series of electrical tests. Finally, the boards are sent to a storeroom.

The plant consists of workareas which are capable of performing 85 distinct operations. 165 different board routings, subsets of the operations implemented in specific sequences, produce 80 distinct board types. Approximately 2200 boards are produced weekly.

At the beginning of each week orders are received and boards are scheduled to be entered into the line. The board mix, i.e. the number of orders for each type of board, is determined by customer demand. The plant supervisors develop a schedule based on a balancing of resource requirements with the board demand. The boards themselves are not the final product of Italtel; rather, they are components of large digital switching systems which are assembled at another Italtel plant. Thus, lack of a single board type can mean delay for an entire system.

There are a number of factors which complicate the situation, both for the plant operation and for simulation:

- Dynamic Part Routings: Decisions are sometimes made dynamically to determine whether automatic or manual operations should be performed. These decisions are based on the dynamic state of the shop, e.g. A large queue for an automatic operation may prompt the moving of boards to an equivalent manual operation.

- Worker Scheduling: 120 workers are employed in six partially overlapping shifts. The number of workers present at any time is insufficient to cover all of the workstations simultaneously. Therefore, dynamic assignments of operators to machines must be made by the supervisors based on current requirements.

- Part Aggregation/Deaggregation: During some operations boards are processed individually, at others they are processed in sublots, i.e. groups of 10 boards, and at still others they are processed in lots, i.e. groups of 4 to 10 sublots. In practice, this approach has provided high utilisation of resources and helped to lower the throughput time of certain orders. However, it has also produced significant ramifications on the scheduling of boards.

- Machine Downtime: As with most manufacturing plants, machine failures introduce disturbances in processing. In most cases, when a machine breaks down there is an alternative machine. However, long queues will often result from machine downtime. A problem for simulation modeling is that records of breakdowns and repairs, i.e. Mean-Time-Between-Failures (MTBF) and Mean-Time-Between-Repairs (MTBR), are kept for only a few of the "heavy usage" machines in the PCB plant.

- Engineering Changes: Occasionally, the design specification for a board type is changed "on the fly." This might require that boards in progress will need be reworked to meet the new specification.

- Missing Components: Components are sometimes unavailable when required on the production line, usually due to problems with an external supplier. Certain board types wait until the component is restocked; others continue through the line and will have the missing component(s) inserted at a later point.

For decision support and record keeping, Italtel employs a software system known as Systar [1]. This system tracks the progress of boards, sublots, and lots at selected operations in the production line. A number of crucial pieces of information are derivable from Systar, including snapshots of queues, snapshots of work in process, board routings, locations of particular board types, operator assignments, and average traversal times for boards.

ITALSIM PROJECT STRUCTURE

The Italsim development team consisted of five full-time and two part-time individuals distributed between Italy and England. The project lasted for a total of fourteen months. The following sections discuss the project goals, project phases, and the specific hardware and software employed to develop Italsim.

Project Goals

Building upon the general requirements provided by the Italtel production personnel, the development team identified specific goals for the development of the knowledge-based simulation. These specific goals were:

- Development of an "open" architecture which would support ease of development and maintenance of models. Extensive designing and programming provides many a programmer with interesting work, but these are obviously not desirable characteristics for the end users of a simulation system. The need for intervention of software engineers is a bane of many simulation systems. It was deemed crucial, therefore, to develop a system which would support new model developments and alterations to existing models with a minimum of effort required from software specialists.

- Provision of the ability to simulate two months of plant operation in two hours or less. The "two-months-in-two-hours" rule arose from early conversations with the production personnel. Anything worse than this would jeopardise the willingness of production management to frequently and effectively use the system.

- Provision of the ability to download live production data in order to develop the initial model, as well as to load snapshots of the plant. Use of production data to develop the initial model would provide consistency with existing software; loading snapshots of live plant data would support a powerful "what if" facility.

- Development of a user interface which would allow the production management to execute and experiment with a variety of simulation "scenarios." A number of specific attributes were identified as crucial for the user interface including the ability to modify predefined parameters (e.g. work shifts, various resource allocations) during the execution of the simulation, the ability to experiment with different board mixes, the ability to view the progress of the simulation and the ability to see statistical results both during and at the conclusion of the simulation.

- Development of an intelligent advisor associated with the simulation. One of the most powerful promises of knowledge-based simulation is in its potential to deliver advisory capabilities as a companion to standard simulation [2][3]. For example, one can imagine a system which would automatically guide the user through the standard simulation stages, i.e. model development, validation, execution, and analysis, and perform a qualitative analysis on the simulation results. Although this goal was not viewed as feasible for the phase of development described in this paper, it was nevertheless identified as an objective for continued work on the system.

Project Phases

Segmentation of tasks arose both from the above goals and from the need to support distributed development, i.e. between Italy and England. This segmentation led to a project structure which occurred in four distinct phases:

- Knowledge Acquisition: This phase consisted primarily of meetings with the plant supervisors and domain experts. The principal purpose was to obtain requisite domain knowledge. Extensive documentation was collected and collated for future reference [4]. The total time required to complete this phase was three months, occurring partially in Italy and partially in England.

- Development of the Integrated Modeling Package (IMP): The project team in England was responsible for the development of a software modeling package to be used as the framework for the Italtel PCB model. The choice to develop a new modeling package was based on the lack of an existing knowledge-based modeling package which would meet the objectives of the project. This phase lasted five months in England.

- Technology Transfer: The objective of this phase was to have the developers of IMP transfer the modeling software, as well as their knowledge of the package, to the team in Italy. The intention was to provide training so that the team in Italy would be able develop a detailed model of the PCB plant. In addition, knowledge on how to augment the IMP software was imparted. Finally, testing of IMP's flexibility on some of the more complex situations in the existing plant occurred. This phase required three weeks and took place in Italy.

- Application Development: This phase occurred in two stages. Stage One focused on design considerations and proceeded in parallel with the development of IMP. During the initial stage the team in Italy designed a user interface, identified the statistics which would prove most useful to the plant supervisors, and analysed the existing tracking system for its use in conjunction with the simulator. After the Technology Transfer phase was completed, Stage Two of the Application Development commenced. The team in Italy used the final six months of the project to augment IMP, to develop a detailed model of the PCB plant, to implement the user interface, to validate the accuracy of the simulation, and to integrate the simulation with the tracking system.

Hardware and Software Environment of Italsim

Italsim was developed on a Texas Instruments Explorer (TM) [5] using Knowledge Craft (R),Simpak (TM), and Graphpak (TM), software products of Carnegie Group Incorporated. Knowledge Craft [6] is an expert system tool kit based on the Common

Lisp language. Knowledge Craft provides a powerful knowledge representation language, multiple programming approaches, i.e. forward and backward chaining and procedural, and interface building tools. Simpak and Graphpak [7] are provided as utilities to Knowledge Craft for use in the development of simulation software. Simpak provides a range of statistical functions, an object-oriented programming language, and a discrete-event calendar mechanism. Graphpak provides graphical utilities used for monitoring simulation and developing user interfaces.

MODELING IN ITALSIM: AN OVERVIEW OF IMP

The Integrated Modeling Package (IMP) is described in detail in [8]. This section provides only an overview of the package.

Rationale for the Development and Use of IMP

Conventional simulation systems tend to suffer from at least one of two major drawbacks: difficulty of use, e.g. need for low-level programming in a Fortran-like language, and inflexibility, e.g. providing for setting of a fixed number of parameters to control simulation. The promise of a knowledge-based simulation is to remove both of these drawbacks. As with most knowledge-based systems, a penalty often paid is increased execution time.

One of the major objectives of the Italsim project was, therefore, to strike a compromise. A search ensued for an existing knowledge-based modeling package which would alleviate the drawbacks while avoiding severe run-time inefficiencies. Only research-oriented and/or commercially unavailable systems [2][3][9][10][11] appeared to exist, so it became obvious that an internally developed package would be required. By focusing on the development of a modeling package, IMP, which was directed toward the manufacturing domain, it was hoped to attain flexibility and ease of use while providing adequate efficiency for use in complex, real-world situations.

Basic Architecture of IMP

IMP provides a set of modeling primitives common to production environments, such as workplaces, storages, resources, and activities. These primitives communicate with each other by using a precisely defined object-oriented protocol. Each primitive actually represents a class of objects. For example, the resource class is subdivided into a number of subclasses, including machines and operators.

The model builder develops a model by instantiating existing objects and by specifying the way in which the instantiated objects connect with one another. For example, an instantiated activity may be connected to an instantiated workplace. In addition, the model builder is provided with the ability to easily augment the existing class hierarchies by defining domain-specific specialisations. In the Italtel PCB model, for example, a simple-activity object was defined which sacrificed the generality of a generic activity in return for a significant increase in run-time speed.

Briefly, the following are the primary IMP objects and their functions:

- Workplaces define logical or physical workareas in a plant.

- Activities represent the operations which occur at workplaces. These are essentially "programs" which define the input, output, and processing of operations.

- Parts flow through the simulation and are processed and (possibly) transformed by activities.

- Storages retain parts which are not being processed at workplaces. Storages control the dispatching of parts, e.g. LIFO, FIFO, to subsequent workplaces.

- Resources are objects which are required by activities to perform processing. Examples of resources are tools, machines, and operators.

- Resource Managers retain resources which are not being used by workplaces and control the dispatching of resources, e.g. FIRST-AVAILABLE, LEAST-LOADED, to subsequent workplaces.

- Transfer nodes control the movement of resources and parts between workplaces and storages.

- Message handlers are responsible for informing resources of their availability/unavailability. Work shifts and machine downtime are examples of message handlers.

An additional salient feature of IMP is its expressive temporal representation. Most simulation systems provide obscure number schemes for representing domain temporal considerations. This is generally simple to implement but limited in expressiveness. The problem of representing absolute and relative events is not easily achieved within these systems. For example, without explicit object representation, how can "daily shifts" or events to occur in "one month" be expressed? IMP provides a calendar based time representation which provides a natural means to specify these and other temporal considerations.

The PC-based simulation attempted by Italtel suffered greatly from inflexibility. There are many aspects of the Italtel PCB plant which could not be directly modeled by the provided primitives. For example, the concept of work shifts was not provided. Thus, shifts had to be approximated by juggling the processing speed of operations. Other factors, e.g. machine downtime, resource sharing, were approximated in a similar manner. As a result, many complex and interacting events had to be modeled by "massaging" numerical parameters. In reality, these events may have complicated interactions with one another, thus the inaccuracies of the approximations multiply.

Of course, in any simulation simplifications are required. But by explicitly providing for common features of manufacturing domains, IMP reduces the number of required simplifications. In addition, the fact that all of these characteristics are explicit objects in the knowledge base supports straightforward modification.

DEVELOPMENT OF ITALSIM

Having completed the modeling package, the task of developing the application system confronted the Italsim team. Development of the system consisted of essentially three subtasks:

- Augmentation of IMP to support the Italtel PCB model building

- Development of the Italtel PCB model (henceforth referred to as the Italsim model) and

- Development of a user interface for the system.

The following sections describe the results obtained through work on each of these subtasks.

Augmentation of IMP

As mentioned previously, the model builder has the option to augment IMP by defining specialisations of existing objects. This characteristic is beneficial because it provides, with a minimum of effort, the ability to tailor the modeling components to meet the requirements of a particular domain. The functionality and default protocol of the existing components may be largely retained and unaltered; extended functionality may be added to meet special requirements. For the development of the Italsim model two classes of augmentation, simplification and automation, were applied.

Simplification was used in cases where run-time efficiency was preferred to the generality provided by the standard IMP objects. To identify candidates for simplification, an initial, fully detailed model of the Italtel domain was developed. The metering utility of the Explorer work station was then employed to help in identifying the costly aspects of the model. One culprit, the activity, has already been mentioned. Development of a simplified form of the standard activity resulted in significant efficiency improvement. Another simplification dealt with the aggregation/deaggregation process of the Italtel plant. Lots and sublots of boards are frequently deaggregated into their constituent sublots and boards and, subsequently, aggregated back into their original grouping later in the processing. It was discovered, however, that only deaggregation was necessary to accurately model the plant. A new type of storage was created, therefore, to take advantage of this discovery. The new "deaggregation only" storage was significantly faster than the general-purpose storage which explicitly performed both aggregation and deaggregation.

Automation was developed by using specialised objects which assisted in extracting data from Systar. The extracted data was invaluable both as a means to develop the static model, i.e. the workstations, operations, and routings, as well as to instantiate dynamic models, i.e. loading of current state information such as the specific boards in a queue. For building of the static model, an IMP utility was developed to convert the relevant Systar information into a skeletal IMP model. Using this skeletal model as a basis, the Italsim team was able to develop the Italtsim model. Perhaps a more crucial augmentation was that which supported extraction of the dynamic, or snapshot, data of the Italtel plant. By specialising a number of the IMP objects, it was possible to map dynamic Systar data into an IMP model. This provided Italsim with one of its most powerful features - the ability to simulate the Italtel plant using live data for an initial simulation state.

The Italsim Model

Development of the Model. As with any simulation model, development of the Italsim model entailed tradeoffs between the dimensions of speed, accuracy, and level of detail. Augmentation of IMP through simplification provided a boost in satisfying the constraint imposed by the "two-months-in-two-hours" rule, but additional simplification was conceivable at a conceptual level. Therefore, the task was to focus on those aspects of the Italsim model which would not suffer from inaccuracy if modeled in an approximate, rather than in an exact, manner. Two aspects of the plant were immediate candidates for approximation based on this criteria. First, it was decided not to explicitly model the movement of the fifty thousand component types. An approximation of this behaviour was sufficient to attain accuracy. Second, in most cases operations needed to be modeled at a great level of detail in order to provide information on bottlenecks; however, the first ten or so operations of the line were clearly never bottlenecks so, therefore, they were modeled as an aggregate "operation."

Aside from these two conceptual approximations of the Italtel plant, as well as the generalisations provided by the simplification of IMP, the Italsim model was developed at a fine granularity of detail. For example, work shifts - including time off for week-ends and holidays - were precisely defined. Most resources, i.e. machines and operators, were explicitly represented. For example, an instantiated IMP object was defined for each of the 120 plant workers. Although the plant supervisors were not directly modeled, worker assignments and scheduling was modeled by definition of resource managers used to control the movement of operators. A simple algorithm provided a good approximation of the heuristic employed by the supervisors. Finally, machine downtime was modeled according to statistics (when available) kept at the plant. Additionally, early knowledge acquisition provided the information necessary to specify whether resources which go out of service, i.e. downtime, are to be waited upon or replaced by new resources.

Among the features of the plant not modeled were Engineering Changes, transportation, and missing components. ECs were judged to be rare enough not to be considered. In a vast majority of cases consecutive workstations are in close proximity, so, therefore, the amount of time required to transport parts is insignificant compared to processing time. Missing components are also a reasonably rare phenomenon; thus incorporation of such behaviour would contribute a negligible amount of increased accuracy. However, a means was provided by which the user may interactively specify certain boards (or lots or sublots) to be delayed due to missing components.

The current Italsim model contains 75 storages, 12 resource managers, 20 machines, and models all 120 operators and 80 board types found in the plant. Two months of activity at the PCB plant can be simulated in approximately 50 minutes, better than twice the targeted speed. In an extended test, the simulation ran uninterrupted for an entire week-end and simulated until the year 2000 with no degradation in performance.

Validation of the Model. Having achieved sufficient detail in the model, along with adhering to the "two-months-in-two-hours" constraint, it was important to validate the model along several dimensions. Conversation with plant personnel led to the identification of the following factors as most crucial for validation:

- Work in Process (WIP) for the entire plant and for significant workareas, i.e. suspected bottlenecks.

- Traversal Time through the plant, both as an average for the entire plant and according to specific board types.

- Utilisation of workareas for the entire plant and for individual workareas.

Comparison of Systar statistics collected over a two-year period compared favorably to statistics of an Italsim simulation executed beyond its transient state, i.e. The time period beyond which statistics tended to stabilise. A summary of the entire plant comparison is found in Table 1. A certain amount of discrepancy between the actual statistics and the Italsim statistics was expected due to two unavoidable errors in the Italsim model: use of inexact machine downtime values due to incomplete live data and error in Italsim processing times due to instances of "fudged" information in the Systar data base. Nevertheless, the statistics showed the Italsim model to be within 35% of the actual average WIP, within 17% of the actual average traversal time, and within 14% of the actual average utilisation for the entire plant. Although these statistics fall short of ideal, they show the Italsim model to be within an acceptable range of error as compared to the actual plant and, in addition, display a vast improvement over the accuracy of the PC simulation.

	ACTUAL	**ITALSIM**	**PC SIM**
Average WIP (boards)	7500	5000	400

Average Traversal time (days)	18	15	5
Average Utilisation (pct.)	70	80	90

Table 1: Statistics Comparing the Actual Plant, Italsim, and the PC Simulation for the Entire PCB Plant

The Italsim User Interface

The targeted user group for the Italsim user interface was middle-level managment responsible for making decisions regarding production procedures, i.e. scheduling, workstation assignments, etc. These individuals have the need to initiate, view, and halt the simulation; to alter the model in order to experiment with various parameters; and to view statistics both during and after a simulation session. This section describes how these facilities have been provided by Italsim.

Figure 1 depicts a snapshot of the Italsim user interface during execution of a simulation. The upper portion of the screen, called the Italsim Command Window, contains the commands available to the user. The commands which are available at each point during the simulation are displayed in this region; the system updates command availability based on its current state. The commands may be invoked either through mouse selection or through keyboard entry into the Italsim Text Entry Window at the lower left. If a selected command requires further specification of information to complete invocation, e.g. selection of Simulation Parameters requires selection of specific parameters, pop-up menus appear to provide further user selection. The center and most prominent portion of the screen contains the Italsim Graphical Display Window. The user may optionally select various pieces of information, for example queue length, WIP, and average traversal time, for display in this window during simulation execution. In order to fully support ease of use, pop-up help windows are available for most of the objects displayed on the screen.

The Italsim user interface guides the user through each step of the simulation. Initially, the user is asked to choose an existing model. Italsim next prompts the user for required simulation parameters, e.g. start date, breakpoints, lot size. The user is prompted for information to be displayed in the Italsim Graphical Display Window. The user is then prompted to initiate the simulation. At any point during execution the simulation may be interrupted; after interrupting, the Italsim Statistics Window (see Figure 2) may be invoked to query the current state. The simulation may optionally be restarted at the point at which it was stopped or, alternatively, a new simulation may be invoked.

During a session predefined parameters may be altered to allow experimentation. A single model may be executed with different board mixes; various lot sizes; addition, deletion, or reassignment of operators, machines, or shifts; alteration of routings; and alteration of workplace capacity. In summary, the user interface provides great flexibility in exploring a wide range of scenarios. Table 2 summarises the functionality available in Italsim and compares it to the available functionality in the PC simulation.

	ITALSIM	**PC SIM**
Average WIP Statistics	Yes	Yes
Average Traversal Time Statistics	Yes	Yes
Average Utilisation Statistics	Yes	Yes
Resource Utilisation Statistics	Yes	No
History of Single Part/Resource	Yes	No
Idle Time Identification	Yes	No
Lot Size Experimentation	Yes	No
Resource Experimentation	Yes	No
Shift Experimentation	Yes	No

Table 2: Comparison of Italsim and PC Simulation Functionality

RESULTS OF WORK ON ITALSIM

The results obtained thus far from Italsim have been encouraging, as the system has proven its worth in many respects. The expressive representation facility provided by IMP allowed an initial working model to be created in scarcely two weeks of time. The flexible architecture supported several special cases to be modeled and, in addition, to quickly modify the completed model. As a further illustration of IMP's powerful representation facility, consider the following experiment undertaken by Italtel. Another of Italtel's PCB plants, this one producing radio PCBs, was chosen as a modeling testbed. The model building exercise for this plant required only two days of effort. The radio PCB plant was less complex than the switching equipment PCB plant, but, nevertheless, the speed with which IMP was applied is noteworthy.

Without sacrificing accuracy, the "two-months-in-two-hours" constraint was satisfied. This required a minimal amount of simplifying assumptions and augmentation to IMP. Given the indicated problems of most knowledge-based systems in the area of efficient processing, this was considered a significant achievement.

Another significant result of the Italsim project was the utilisation by the system of existing data base information. By extracting information from the Systar data base, Italsim was able to generate an initial plant model, as well as to load dynamic plant data. The "What if" capability provided by loading of dynamic data has proven to especially helpful in gaining the production personnel's acceptance and use of Italsim.

Perhaps the most powerful contribution of Italsim, provision of an intelligent advisor, is yet to come. This goal was not expected to be met during this initial phase of development, but will now assume heightened importance. The appropriate framework, i.e. the knowledge engineering hardware and software plus the initial functioning Italsim system, is in place to begin focusing on the difficulties of developing an intelligent simulation advisor. Many heuristics employed by production personnel for production planning were acquired during the course of the project; now the task is to implement an appropriate strategy for including these heuristics in the existing architecture.

The system recently moved into the production testing phase, and initial feedback from the production supervisors has been positive, both in terms of the systems usability and accuracy. Based on the comments received from production personnel, and the subsequent refinements elicited from these comments, optimism prevails that Italsim will be used as a regular production tool in the near future.

In conclusion, the functionality and accuracy of Italsim have proven to be significantly better than the PC approach previously attempted by Italtel. More importantly, the system is rapidly moving towards acceptance by production personnel as a valuable production planning tool. In addition, Italsim holds the future promise of providing intelligent production assistance not ordinarily found in simulation software.

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Figure 1: The Italsim User Interface

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Figure 2: The Italsim Statistics Window

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