NET WMS

Networked Businesses in WMS

Towards integrating virtual reality and optimisation techniques in a new generation of **Net**worked businesses in **W**arehouse **M**anagement **S**ystems under constraints

Final Project Report

Project fact sheet

Project acronym: Net-WMS

Project full Title: Towards integrating Virtual Reality and optimisation techniques in a new generation of Networked businesses in Warehouse Management Systems under constraints

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Instrument: Specific Targeted Research Project

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Conception & Realisation: Azur Communications
Photos: IStock/ Matthias Hass, Tony Tremblay

Introduction

Networked Warehouse Management System:

Integrating Optimisation and Virtual Reality components in a new generation of networked warehouse management systems.

Net-WMS is a Specific Targeted Research Project (STREP) co-funded by the European Commission in the sixth Framework Programme. The project lasted 40 months, from September 2006 to December 2009.

The main objective of Net-WMS is to significantly increase the competitiveness of Supply Chain Management through the integration of novel optimisation and virtual reality components in a Warehouse Management System (WMS). A networked WMS will lead to think, specify and structure the warehouse management process and map it into a distributed environment by using the state of the art of ambient intelligence technologies.

This brochure presents the partners of the Net-WMS consortium as well as its activities and achievements over the forty months of its EC-funded life time.

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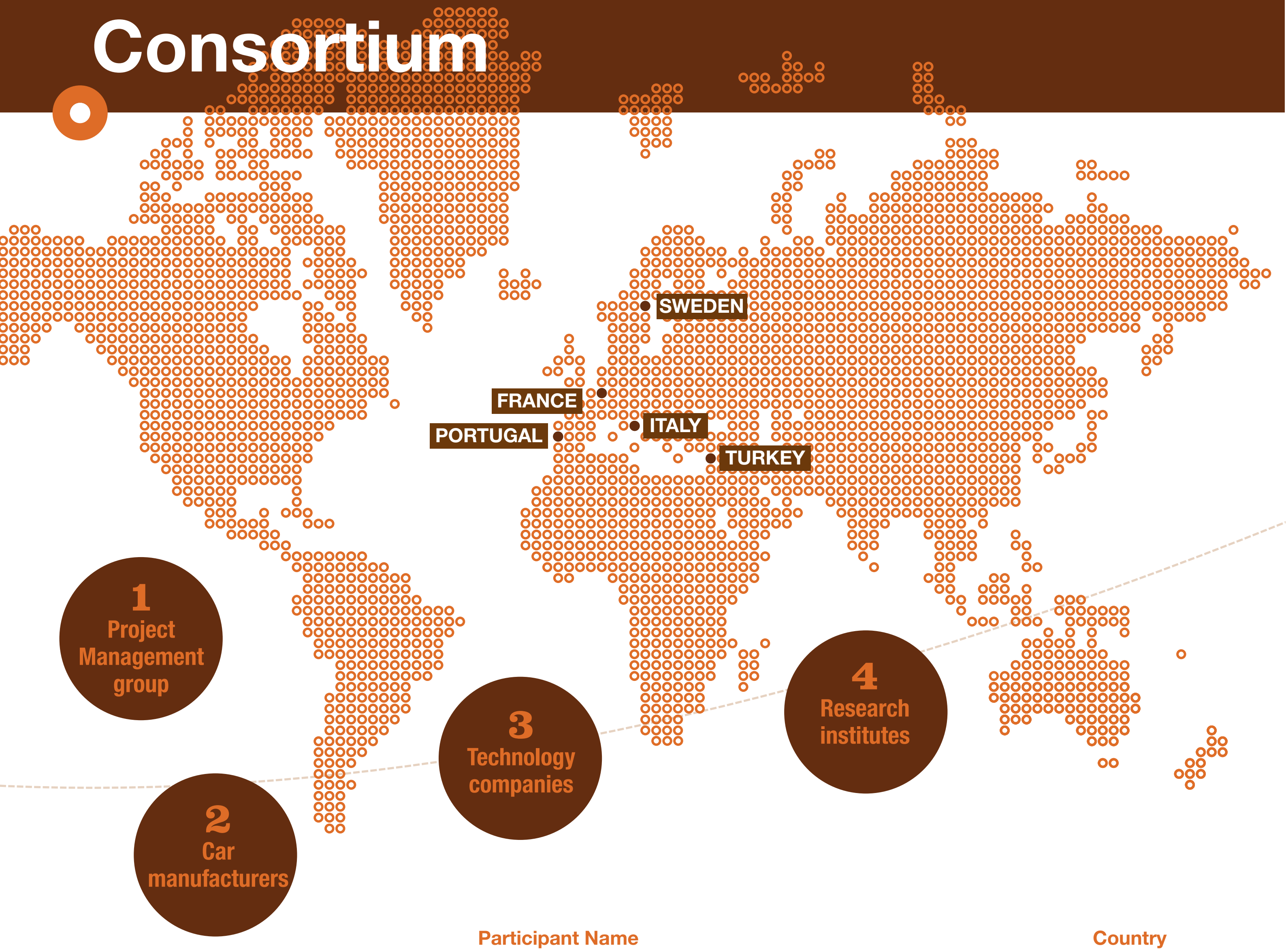
Consortium



Participant Name	Country
GEIE ERCIM European Research Consortium for Informatics and Mathematics	France
INRIA National Institute for Research in Computer Science and Control	France
CEA-LIST Atomic Energy Commission - Laboratory of Applied Research on Software-Intensive Systems	France
ARMINES Ecole des Mines de Nantes	France
SICS Swedish Institute of Computer Science	Sweden
PSA PSA Peugeot Citroën	France
CRF Società Consortile per Azioni, FIAT Group	Italy
KLS OPTIM	France
Mind2Biz Bilişim Teknolojileri Danışmanlık Hizmetleri	Turkey
Wide Scope	Portugal

Executive Summary

Vision

The supply chain of a manufacturing enterprise is a world-wide network of suppliers, factories, warehouses, distribution centres and retailers through which raw materials are acquired, transformed and delivered to customers. The organisation is so complex that the complete process is structured into a chain of interconnected modules. Each module can be associated to a business sector. In order to optimise performance of the complete process, supply chain functions must operate in a coordinated manner.
Existing Warehouse Management Systems (WMS) provide advanced features to manage the movement of items within the warehouse, but fail to comply with the increasing demand on more numerical handling. Generally, WMS are lacking optimisation functionalities and advanced packing tools for determining how to pack items on a pallet, how many cartons are needed to pack customer items, how to pack pallets in a truck according to stability constraints and to the customer to visit, how to redesign a storage area, an assembly line, etc.

The vision of the Net-WMS project is that these hard combinatorial optimisation functionalities can be addressed in a new generation of WMS with advanced software technologies combining rule-based knowledge representation, constraint programming optimisation, virtual reality interactions, and service oriented architecture.

Achievements

Nine test applications have been developed for evaluating and promoting the capabilities of the Net-WMS methodology. These test cases have been defined by the industrial partners of the project, PSA Peugeot Citroën, CRF Fiat Research Centre and KLS OPTIM, constituting a representative variety of pallet loading, container loading and assembly-line design problems. Beyond the evaluation purposes of the Net-WMS technology, these use cases represent demonstration prototypes and illustrate how Net-WMS middleware components can be exploited in real world scenarios.

To achieve the end-user application objectives, the first scientific objective of Net-WMS was to make advances in the field of combinatorial optimisation by developing constraint programming techniques for bin packing, bin design and more generally placement problems. The geometrical kernel developed by ARMINES and SICS for multidimensional non-overlapping constraints is an outstanding contribution which is the object of a series of publications concerning:

- Strong necessary conditions for non-overlapping and re-use of global constraints,
- Filtering algorithms,
- Greedy heuristic use of the constraint,
- Evaluation on public benchmarks and on pallet loading problems.

The constraint geost, which implements these new algorithms, has been released by SICS in SICStus Prolog http://www.sics.se/sicstus, by ARMINES in the last version of the open source software Choco http://choco.emn.fr, and in the general catalogue of constraints

http://www.emn.fr/x-info/sdemasse/gccat/titlepage.html, making this work visible and available to a wide audience.
A second objective of the project was to make constraint programming easier to use in the industry by designing a knowledge modelling language providing a very high level of abstraction for specifying bin packing and bin design problems and solving them transparently with constraint programming techniques. The Packing Knowledge Modelling Language PKML has been designed for the Net-WMS needs as a particular case of a general rule-based modelling language for constraint programming, developed by INRIA and named Rules2CP, bridging the gap between business rules and constraint programs. It has been shown by SICS, INRIA and ARMINES that a large subset of PKML can be compiled directly into the geometrical kernel of geost for best efficiency. This work has been presented in several international meetings and is implemented in open-source http://contraintes.inria.fr/rules2cp .

A third objective of Net-WMS was to make constraint-based optimisation specifically easier to use on placement problems by developing virtual reality concepts for solving packing problems, including 3D visualisation of objects, simulation of laws of physics applied to the objects, and combining the capabilities of virtual reality and optimisation to provide the most efficient assistance to the packing planner. The virtual human worker developed by CEA for the CRF study case, and the prototypes of the collaborative system between the user and optimisation components developed by CEA and KLS OPTIM for the PSA study cases illustrate this highly innovative approach to computing solutions and confirm their validity with respect to extra requirements.

To make all these software components work together in a fully networked and distributed WMS, a solid middleware architecture was the key. Apart from a few standalone applications, all software components developed in Net-WMS have been integrated in a Service Oriented Architecture (SOA). This architecture recommended by Wide Scope, and supported by a J2EE environment, has shown its effectiveness to develop such solutions by encapsulating software components in Java Beans, making them readily interoperable on the web in a transparent manner. This is in sharp contrast with more costly end-user-specific developments and is well illustrated by the application prototypes.

The technological transfer of Net-WMS components is already ensured by their industrialisation by KLS OPTIM in the KLS optimisation suite, and by their integration in the open-source or commercial software of the academic partners. Thanks to this successful technological transfer, the Net-WMS technology is already on the shelf for the market of logistics and warehouse management systems, and a large part of the collaborations between Net-WMS partners is expected to continue beyond the end of the project.

Structure and Governance

Project management is the responsibility of the Finance & Administration Coordinator, who acted as liaison with the European Commission and ensured that:

- The necessary conditions for productive work and delivery of quality results are in place,
- Scientific and technical teams receive the financial and administrative support they need, thereby allowing them to focus on the main project objectives,
- The description of work is adhered to and the liaison with the EC is regularly maintained,
- The quality assurance plan is applied, in particular with regards to the contractual deliverables.

The governance of Net-WMS was exercised via its Scientific Coordinator, its Technical Director, and its Finance & Administration Coordinator.

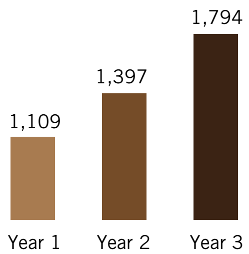
François Fages (INRIA)
Scientific Coordinator

Philippe Rohou (ERCIM)
F&A Coordinator

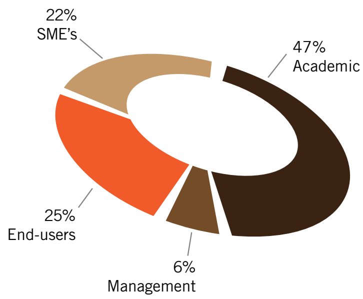
Abder Aggoun (KLS OPTIM)
Technical Director

Together with the Work Package Leaders, they formed the Net-WMS steering committee which was the main decision-making body of the project.

Actual spending per year (M€)



EC funding per type of partner



Use of Resources

The overall effort produced by the consortium to deliver the Net-WMS project results represents an investment of approximately 40 person-years over the full duration of the contract. In financial terms, the actual partners' contribution amounts up to 4.3 M€, resulting in a 54% EC funding. As shown here, the Net-WMS partners ramped up their activity in line with the 3-year work plan: requirements, specifications, prototyping.

On the basis of 4 categories of partners in the project – Management: ERCIM, Academics: INRIA, ARMINES, SICS, CEA, SME's: KLS OPTIM, Wide Scope, Mind2Biz, End-Users: PSA, CRF – one can roughly estimate that the overall effort has been invested half in research and development, a quarter in prototyping, and a quarter in specification and validation. The percentage shown against management includes project coordination and dissemination.

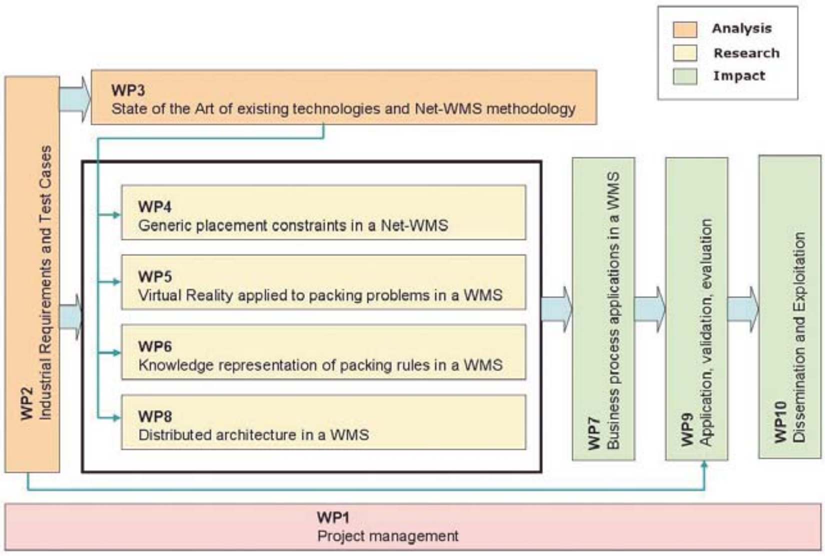
After 40 months of fruitful team activities, Net-WMS has delivered the initially expected results on time and on budget.

Work plan

The Net-WMS work plan consists of ten work packages (WP), each addressing a focused area of the project and calling upon specific expertise to deliver their own building blocks. With the exception of WP1 (Management) which occupies a special transversal position, the nine scientific and technical work packages can be logically viewed as belonging to one of three major areas of activity within the overall scope of Net-WMS:

- **Analysis:** WMS current practices, existing technologies, business cases,
- **Research:** architecture, virtual reality, constraint & rule programming,
- **Impact:** identify candidate applications, validate and disseminate results.

It is along these three main axes that the activities and achievements of Net-WMS are described in the following pages.



Analysis

Industrial Requirements and Test Cases

One of the first activities of the consortium was to define in details the industrial test cases on which Net-WMS would concentrate.
Each industrial partner proposed a set of test cases addressing some concrete problems that they had to solve in their warehouse or on their assembly lines.

PSA Peugeot Citroën

The PSA test case focuses on container loading for the CKD transportation of vehicles.
The vehicles marketed by the PSA Peugeot Citroën group are either manufactured in the group's own factories, or are assembled by a PSA partner from parts of Completely Knocked Down (CKD) or SKD (Semi Knocked Down) vehicles.
PSA subsidiaries in charge of the CKD expeditions conceive and optimise the conditioning and the packing processes. The resulting containers are then delivered by sea, ground or air transportation to the assembly factories, which have the responsibility to assemble or to manufacture the vehicles.
In this requirement phase, PSA has defined the complete set of practices and rules used in the CKD packing process, from the integration of conditioning suppliers to the final loading plan. The main specifications of the prototype aimed at:

- optimising the volumes sent to the assemblers. The reduction of the packing material and the number of containers necessary for the routing is an important factor of profits,
- being much more reactive in taking into account the vehicle evolutions (new parts, change in the rate of local integration),
- re-using existing solutions, thereby generating profits and not questioning currently used optimised processes or industrial devices in place,
- working in simulation mode when the physical parts are not available.

CRF (Centro Ricerche Fiat)

CRF proposed two different but strongly related test cases to be implemented in the Fiat plant. These test cases are partly related to the packing problems identified at PSA and consist in:

- The re-design of the line-side storage, which is a storage area for car parts located alongside the assembly line,
- The design of the preparation area (physical layout, location of containers, etc.) and the validation of different configurations by means of virtual reality and virtual human movements simulation.

The CRF test cases were motivated mainly by a new general strategy of the Fiat plant that aims to reduce the line side stock and low-value activities of the operators. This strategy implies the reduction of material replenishment quantities, and increases the frequency of deliveries in order to maintain the same production volumes. The higher frequency of deliveries requires the support of an efficient automated scheduling tool. Within the Net-WMS project, prototypes of such decision support tools have been developed for each of the above scenarios. The tools made available by the project allow the plant experts to solve problems independently of each other and to analyse the complex consequences of the decisions made using the Net-WMS architecture.

KLS OPTIM

KLS OPTIM worked on four test cases highlighting the different classes and variants of problems with their respective constraints and objectives. The problems are taken from different sectors of logistics:

- Optimisation of loading plans in production,
- Optimisation of loading plans in distribution,
- Optimisation of vehicle loading plans in distribution,

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(PSA)

Michaël Doussot
(PSA)
CKD expert

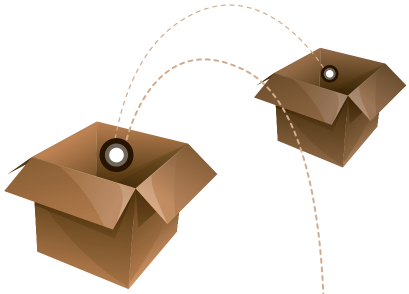
- Optimisation of container loading for export in the wine industry.

Optimisation of loading plans of pallets (large boxes) in production: The problem addressed here is taken from an OEM Manufacturer, a French company supplying products to different car makers. The aim is to design optimal plans to place packs (a set of products) into boxes (large cartons then stacked on wooden pallets). The optimised box is a single reference-pallet, all items are identical. The objective is to solve the problem by selecting the best arrangement of identical packs subject to business constraints like side-up or rotation restrictions, height overlay (possibility to exceed the total height of the box within a limited length) , etc.

Optimisation of loading plans of pallets in distribution: This application is taken from an international company which delivers a fully integrated logistics solution and which is recognised as one of the leading logistics providers in the market. This company offers a diverse range of logistics services including warehousing and distribution, freight forwarding, international network solutions, supply chain consulting, and IT solutions. The problem addressed here addresses warehousing and distribution. It concerns the order preparation of large orders for intermediate platforms or important customers like manufacturers in various sectors. An order is a set of lines. Each line describes the ordered product with its corresponding quantity. A carton in a pallet may have up to six possible orientations which may increase complexity in some cases. The problem consists of packing boxes of various sizes onto available pallets (large boxes) in a way which optimises the total number of pallets subject to constraints like orientation, fragility, stackability, weight, volume constraints, etc.

Optimisation of vehicle loading plans in distribution: This application is complementary to the previous two above. It takes as input the total number of pallets and computes the optimal linear meters for vehicle loading. The aim is not to compute the loading plan for a given vehicle but rather the optimal loading of a virtual vehicle subject to constraints like orientation, stackability, weight, volume constraints, as well as preferences like priorities and order of deliveries.

Optimisation of container loading for export in wine industry: This application is taken from a small SME company which specialises in container export for the wine industry. The aim is to maximise the load of containers subject to constraints like orientation, fragility, stackability, weight, etc. The variety of cases might change from one load to another. In addition, dedicated strategies are required (packing by piles, less small holes) to improve the quality of loads and the safety (less damage) during the transport.



Analysis

State-of-the-Art of Existing Technologies and Net-WMS Methodology

Supply Chain and Warehouse Management Systems

The term Supply Chain Management (SCM) was coined by consultant Keith Oliver, of strategy consulting firm Booz Allen Hamilton in 1982. Supply Chain Management is structured into complementary processes of planning, implementing, and controlling the operations of the supply chain with a view to satisfy customer requirements as efficiently as possible.

A Warehouse Management System (WMS) is used to control and monitor the main operations of the warehouse like handling reception, processing orders, order picking, order shipping and inventory management. Indeed, the basic logic in handling a warehouse is the capability to exploit a combination of item, location, quantity, inventory, unit of measure, resource, order information and activity to determine where to pick, how to pick and in what sequence to perform these operations.

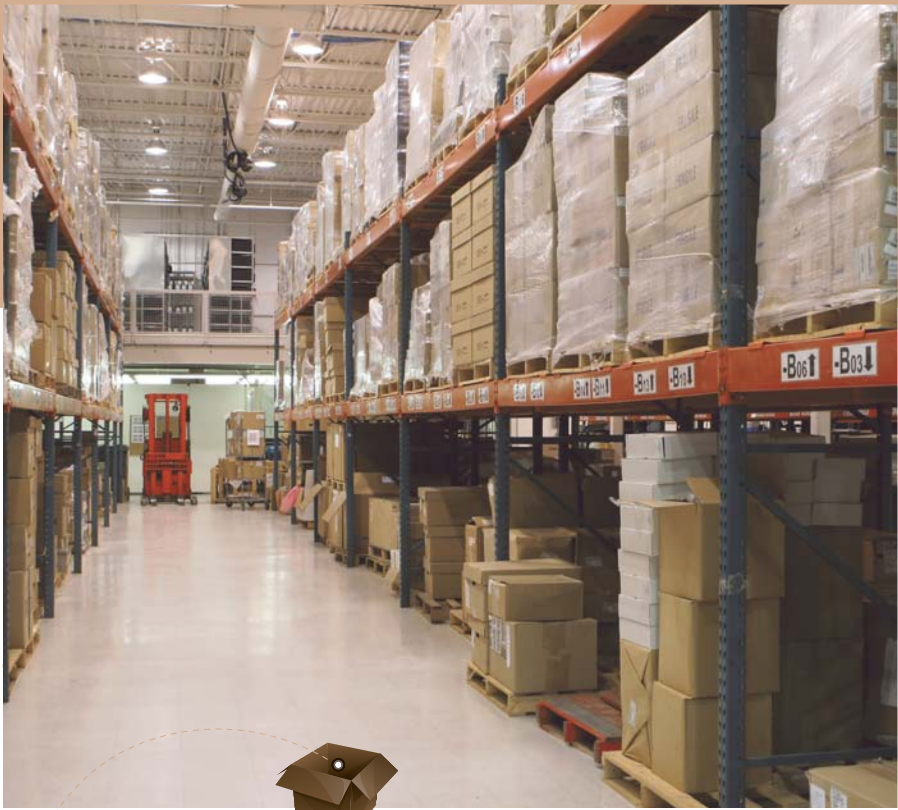
The process in a WMS is built around the following basic functionalities:
• Inventory Control,
• Storage Location Management,
• Quality Control Interfacing,
• Order Selection,
• Automated Inventory Replenishment,
• Receiving,
• Shipping,
• Operator Productivity,
• Report Generation,
• Preparing activities of orders,
• Manual scheduling of activities.

Existing WMS provide advanced features to manage the movement of items within the warehouse, but fail to comply with the increasing demand on more numerical handling, such as: how to pack items in a container, number of cartons needed to pack customer items, how to schedule the manpower to finish the preparation in time, in which order to pack items in a pallet, and the position of pallets in a truck according to the customers to visit. Generally, all existing WMS are lacking optimisation functionalities like planning, scheduling, advanced packing tools, optimal filling of containers and trucks subject to delivery constraints. Advanced packing functionalities are lacking in most existing WMS available on the market.

Expected new functionalities thus concern:
• Packing activities of orders,
• Loading activities,
• Vehicle handling (assigning orders to vehicles),
• Gate handling (assigning vehicles to gates),
• Automatic scheduling of activities,
• Intranet and internet capabilities.

Packing Optimisation

The bin packing problem is a classical combinatorial optimisation problem that has contributed to the development of the theory of algorithms and complexity since the early 1970's. This problem is furthermore of great practical importance. It is the central problem of many industrial applications, such as loading and placement problems for which the bins represent trucks, containers or warehouses, and the items represent the pieces to be loaded according to weight, length, surface or volume constraints. It is thus a core problem for the numerical handling and optimisation of warehouse management. The one-dimensional bin packing problem (1BP) is, given
Input: N items of length L1,...,LN to pack in K bins of length L
Output: a packing if one exists (decision problem), or the minimum value K* of K for which there exists a solution (optimisation problem).
1BP directly models simple forms of truck loading or assembly line design problems. It is however a NP-hard problem which means that no efficient polynomial-time algorithm exist for solving all instances of this problem, if we admit the conjecture $P \neq NP$.
Two-dimensional (2BP) and three-dimensional (3BP) bin packing problems model many loading problems, respectively by layers or directly in space. These problems contain many variants according to the shapes allowed for the items (squares, rectangles, orthotopes, etc.), and whether or not items may be rotated. All these variants have the same theoretical complexity (NP-hard) as long as a grid of integer coordinates and a finite number of



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(KLS OPTIM)

rotations are considered for the packing. The core container loading and pallet loading problems are 3BP problems, but while in bin packing the only objective is to achieve high volumetric use, the real problems require additional constraints of gravity, as well as some additional requirements coming from the practical applications. Examples of such additional requirements are the stacking conditions, container stability, visibility and accessibility considerations, or different rules that address the prevention of damage or constrain the loading sequence. The significance of considering these practical requirements in addition to the volumetric use, especially the weight distribution in container loading, has been emphasised by many authors and it is a primary objective of Net-WMS to advance the state-of-the-art in this domain.

Constraint Programming

Constraint programming is a declarative programming paradigm which relies on two components: a constraint component which manages posting and checking satisfiability and entailment of constraints over some fixed computational domain, and a programming component which assembles the constraints of a given problem and expresses search procedures. Because of its capability to handle a great variety of specific requirements, the main technical approach developed by the Net-WMS project to solve packing problems is based on constraint programming, with the aim of making significant advances on the design and implementation of efficient geometrical constraint solvers in this context.

The expression of packing knowledge and industrial requirements in a suitable form, both for non-programmer packing experts and for its automatic translation to efficient constraint programs, is a second main challenge addressed in Net-WMS. Because of its capability to represent independent pieces of knowledge declaratively, a rule-based formalism capable of expressing packing business rules is investigated in the project as a knowledge representation language and as a new general purpose modelling language for constraint programming.

Virtual Reality

The modelling and computational complexity of optimisation problems encountered in WMS also shows that not all problems can be solved fully automatically and that efficient interaction means with the user are mandatory in many cases. In this respect, a third challenge of Net-WMS was to investigate the connection of Virtual Reality concepts and tools to optimisation components, in order to drive the computation of better solutions in hard cases, and get more information on human factors and the effect of laws of physics in the computed solutions.

Service Oriented Architecture

Networked architectures play an important role in current technology information systems, and constitute a crucial aspect of supply chain management. The industry requirements include highly available, secure, portable, reliable and scalable services that integrate distinct enterprise information systems and provide several front-ends for users across a network. J2EE is a middleware architecture for developing and deploying multitier, distributed, enterprise-scale business applications. Applications that follow the J2EE standards inherently benefit from features such as scalability, portability, reusability, security, and load-balancing. For these reasons, most components developed in the Net-WMS project have been designed as middleware components in a networked J2EE architecture.

Research

Generic Placement Constraints

Objectives

The objectives of this Net-WMS research module were four-fold:

- Defining a geometrical kernel for handling multidimensional placement problems involving rectangular shapes,
- Handling a large variety of packing problem (e.g., 2D, 3D, 3D+time),
- Integrating the geometrical kernel in a smooth way in several existing constraints toolkits,
- Handling side constraints in this open kernel (i.e., business specific constraints).

Results

Once achieved, these objectives have produced the following significant results for the project:

- A global constraint based encapsulated geometrical kernel (geost),
- A generic multidimensional sweep based algorithm that can handle a variety of geometrical constraints in a uniform way,
- Three concrete implementations of geost: two within the project (inside the open source CHOCO library and inside SICStus Prolog) as well as one outside the project (inside the JaCoP open source library),
- A greedy mode for handling problems with up to several million objects,
- An integration within the commercial products of one of the project partner (KLS OPTIM),
- Academic open problems closed:
  - Partridge for n=12
  - Smallest square for packing rectangles with distinct sizes for n=9 ,
- Peer-reviewed academic publications.

Activities

Packing subject to specific constraints is ubiquitous to many practical problems that arise in the context of a WMS. The goal of this research area within Net-WMS was to provide a flexible geometrical kernel that could directly handle a large class of this type of problems. The kernel should be general enough so that:

1. one can plug problem-specific heuristics dedicated to specific packing problems,
2. one can add business rules expressing problem-specific packing constraints,
3. one can embed this packing component within other solvers used for handling other aspects such as computing routes for distributing and/or collecting products.

As illustrated in Figure 1 in the context of non-overlapping, geost allows direct modelling of a large number of placement problems:

- **Case (A)** corresponds to a non-overlapping constraint among three segments,
- The second and third **cases (B,C)** correspond to a non-overlapping constraint between rectangles where (B) is a special case where the sizes of all rectangles in the second dimension are equal to 1; this can be interpreted as a machine assignment problem,
- **Case (D)** corresponds to a non-overlapping constraint between rectangles where each rectangle can have two orientations. This is achieved by associating with each rectangle two shapes of respective sizes l x h and h x l. Since their orientation is not initially fixed, the included constraint enforces the three rectangles to be included within the bounding box defined by the origin's coordinates 1,1 and sizes 8,3,
- **Case (E)** corresponds to a non-overlapping constraint between more complex objects where each object is described by a given set of rectangles,
- **Case (F)** describes a placement problem where one has to first assign each rectangle to a strip so that all rectangles that are assigned to the same strip do not overlap,
- **Case (G)** corresponds to a non-overlapping constraint between orthotopes,
- **Case (H)** can be interpreted as a non-overlapping constraint between orthotopes that are assigned to the same container. The first dimension corresponds to the identifier of the container, while the next three dimensions are associated with the position of a orthotope inside a container,
- **Case (I)** describes a rectangle placement problem over three consecutive time-slots: rectangles assigned to the

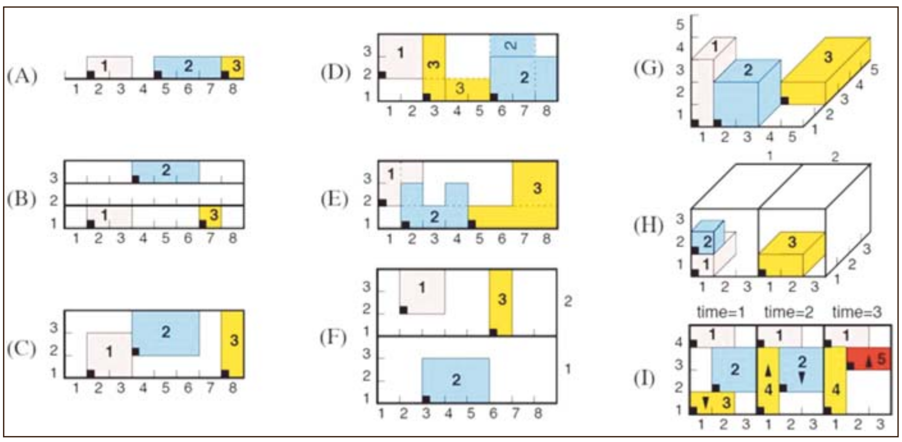
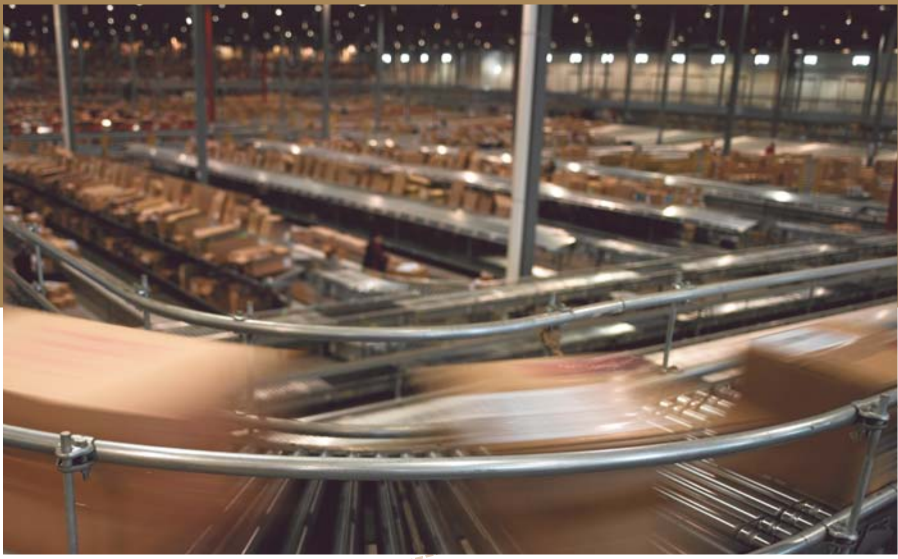


Figure 1: typical placement problems handled by geost



WP leader:
Nicolas Beldiceanu
(ARMINES)

same time-slot should not overlap in time. We initially start with the three rectangles 1, 2 and 3. Rectangle 3 is no longer present at instant 2 (the triangle within rectangle 3 at time 1 indicates that rectangle 3 will disappear at the next time-point), while rectangle 4 appears at instant 2 (the triangle within rectangle 4 at time 2 denotes the fact that rectangle 4 appears at instant 2). Finally, rectangle 2 disappears at instant 3 and is replaced by rectangle 5.

Constraint programming was selected as offering a flexible environment for developing such a constraint kernel. More precisely we chose to embed the geometrical kernel within a generic global constraint, named geost, so that it could be used with all standard available constraints of a typical constraint toolkit (CHOCO and SICStus in our context). The geost constraint is generic in the sense that it can handle the location in space of polymorphic multidimensional objects subject to various geometrical constraints.
A first significant effort in this research was the development of a multi-dimensional sweep based algorithm that could handle a large class of geometrical constraints in a uniform way. A second significant effort was the development of efficient methods for handling multidimensional non-overlapping constraints. In this context, general necessary conditions were developed, especially cumulative necessary conditions for non-overlapping. Necessary conditions for important sub cases (e.g., pallet loading) were also conceived. Finally, in order to handle the fact that many practical problems consider only a few types of items to place, symmetry breaking techniques that directly consider non-overlapping were designed.
The specifications of the geometrical kernel developed in this work package were implemented within the open source CHOCO Java library as well as within the SICStus Prolog platform. Finally a third implementation was done outside the Net-WMS project within the open source JaCoP constraint library.

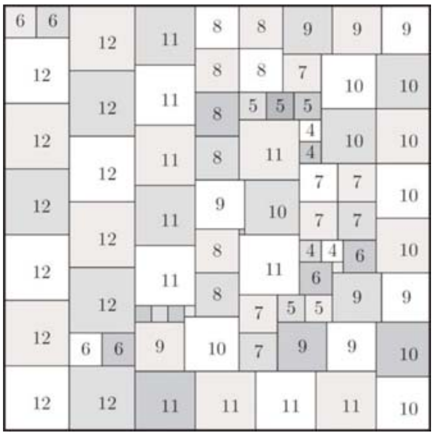


Figure 2: A solution found by geost to the Partridge problem for n=12

Links to the geometrical kernel geost

CHOCO
http://choco.emn.fr/

JaCoP
http://jacop.cs.lth.se/

SICStus
http://www.sics.se/sicstus/

Constraint Catalog
http://www.emn.fr/x-info/sdemasse/gccat/

geost in CHOCO
http://www.emn.fr/x-info/choco-solver/doku.php?id=geost

geost in JaCoP
http://jacopapi.osolpro.com/JaCoP/constraints/geost/Geost.html

geost in SICStus
http://www.sics.se/sicstus/docs/latest4/html/sicstus.html/Combinatorial-Constraints.html

geost in Constraint Catalog
http://www.emn.fr/x-info/sdemasse/gccat/Cgeost.html

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Virtual Reality Applied to Packing Problems

Virtual Reality (VR) covers a set of techniques that allow a human to interact with a virtual environment (created and managed by computers) while feeling like being immersed inside it. In the frame of warehouse management, VR was considered for several purposes:

1. Visualise in 3D both the packed and packing objects (items and bins) as virtual packages,
2. Interact with virtual packages, mainly loading, unloading and positioning virtual items,
3. Plan packing configuration through realistic or metaphoric operations (like "put the selected item in the next available location at the back and the right side of the bin"), taking into account packing rules (for example "heavier objects should be located at the bottom of the bin"),
4. Provide an intuitive 3D interface for the optimisation solvers with which a human expert could efficiently cooperate,
5. Simulate the laws of mechanics so as to guarantee that virtual packing configurations can be achieved in the real world and to provide some information about the resulting boxes or pallets (like their weight and centre of gravity),
6. Validate packing and unpacking procedures by simulating them with virtual workers.

On the one hand, objectives 1, 2 and 3 clearly stay within the current state of the art in virtual reality. On the other hand, the last three goals are much more ambitious. In particular, objective 4 implies interfacing (i) the real warehouse environment captured in the virtual world with continuous translations/orientations and complex shapes, with (ii) its mathematical optimisation model featuring ideal objects, as well as discrete positions and orientations. Nevertheless, the expected benefit is considerable: mixing automatic solving with the human expertise that is able to properly set a difficult problem, to rely on previous experience or to use rules of thumb.

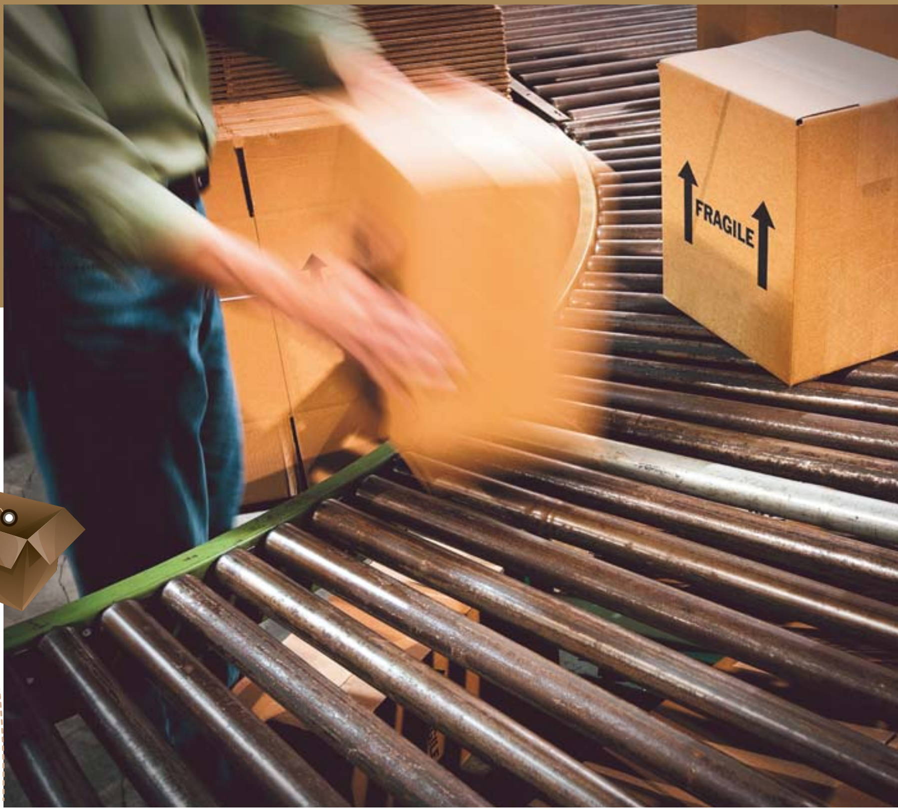
Regarding item 6, the dynamic simulation of virtual humans grasping objects, carrying heavy loads, planning collision-free paths in space, releasing objects, managing their postures and maintaining their balance is a pre-requisite. This cannot be achieved by existing virtual humans animated by inverse kinematics control modes.

In these developments, a major constraint was to focus on end-users that are professionals from the packing field but not VR experts. Additionally, it was mandatory to use only common, low-cost computer systems and interfaces, while providing real time interactions of the human user with the virtual warehouse environment.

The objectives mentioned above were achieved through two software modules provided by CEA. The first one called the Virtual Warehouse is an application designed to assist the humans in charge of planning the packing of cardboard boxes or pallets. The second one simulates loading and unloading operations with virtual human workers.

The Virtual Warehouse is firstly a VR application that allows a human operator to handle virtual packages: select bins, select items and define packing configurations. It is thus interfaced with external databases describing bins and items and with automatic solvers that may be called to provide complete or partial solutions to the considered packing problems. Its main functions are:

- Packing problem loading and configuration saving,
- Display information on virtual packages:
  - 3D views observed from a viewpoint under operator control,
  - 2D views (typically slices) as selected by the operator,
  - Tabulated description of objects (items and bins) associated with their main data,
- Object designation,
- Object placement:
  - Manual placement of one item (using mouse or keyboard),
  - Automatic placement of one item (using buttons provided by the interface),
  - Optimised placement of a set of items (relying on the capabilities of the automatic solvers),
- Basic physical simulation:
  - Collision detection and management,
  - Gravity,
- "On-line" checking of packing rules (in order to inform the operator when the achieved configuration infringes some packing rules),
- Configuration management:
  - Freeze a partial configuration,
  - Undo,
  - Backtrack on an optimised configuration.



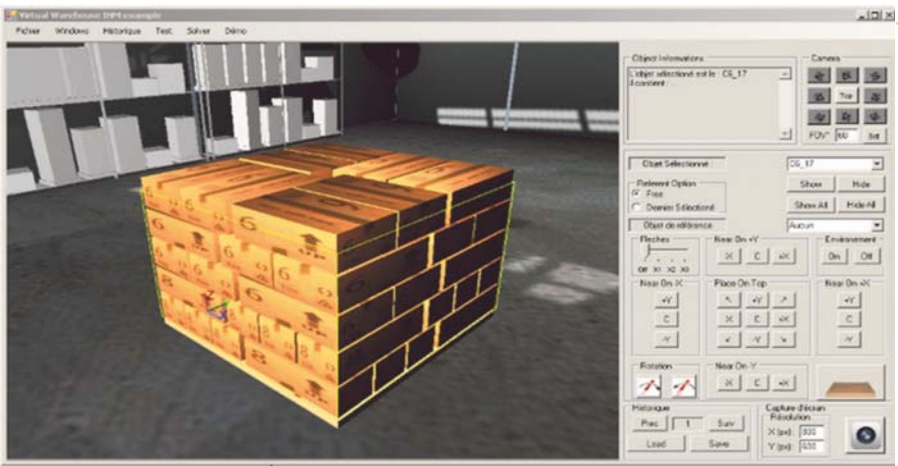
WP leader:
Philippe Gravez
(CEA-LIST)

Camille Chigot
(CEA-LIST)

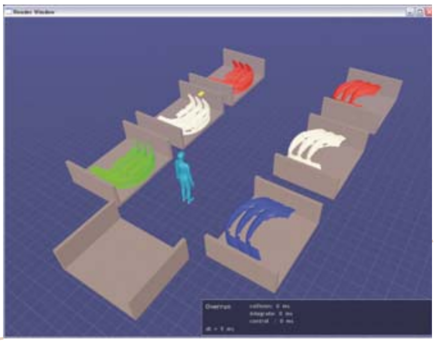
Renaud Deligny
(CEA-LIST)

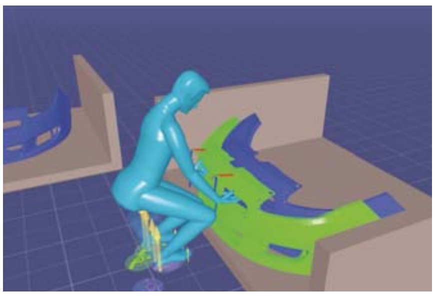
The Virtual Warehouse was developed through several steps. It started with the implementation of a stand alone mock-up to test the 3D manipulation of boxes in the Net-WMS context and to demonstrate it to the project end-users. The next step was the detailed specifications of the Virtual Warehouse functions and the interface between the Virtual Warehouse and the optimisation solvers (INRIA and CEA). Based on these specifications, a complete prototype emerged. It was coupled with an external database and an optimiser module provided by KLS OPTIM. In this configuration, it was transferred to the end-users for evaluation. As described later, the man-machine interface of the prototype was extensively re-designed by PSA to better suit the requirements of its packing experts. In its final state, the Virtual Warehouse seems to satisfactorily fulfil the expectations of the end-users.

Beside the development outlined above that led to a fully operational system, the second application of VR techniques addresses the simulation of packing and unpacking tasks with virtual workers in order to validate either a packing configuration or a packing workstation. The developed module describes a preparation area in a car factory (test case provided by CRF): bumpers with different colours, unloaded from containers provided by suppliers, are put in an ordered way inside the container that will be sent to the assembly line. The goal is to verify that the available space is sufficient for the worker to perform his task. This application was made possible by recent progress in the fields of fast collision detection, real-time mechanical simulation, path planning in 3D space and optimisation-based manikin control taking into account balance and posture management, locomotion and grasping.



The Virtual Warehouse mock-up.





Preparation area simulation: the virtual manikin walks towards the box selected by the user, grasps a bumper, finds a path to move towards the assembly line container and releases the bumper inside it.

Knowledge Representation of Packing Rules

Objectives

The main objectives of this Net-WMS research module can be summarised as follows:

- Integrate knowledge representation techniques into the area of packing problems,
- Structure knowledge into packing rules
- Come up with a set of generic primitives for packing rules in a WMS,
- Define a rule-based Packing Knowledge Modelling Language (Rules2CP/PKML) for expressing packing problems,
- Transform knowledge expressed in Rules2CP/PKML into executable code,
- Provide support software for working with Rules2CP/PKML,
- Define an XML representation of Rules2CP/PKML.

Results

At the end of the project, some significant achievements can be highlighted:

- The Rules2CP language: a modelling language for optimisation problems,
- PKML - a library module of Rules2CP specialised for packing problems,
- A compiler from Rules2CP into executable Java code using the constraint programming library Choco,
- A compiler from Rules2CP into executable Prolog code using the constraint programming functionality of SICStus Prolog,
- An XML DTD for Rules2CP,
- A graphical user environment for developing, editing and executing packing knowledge,
- Peer-reviewed academic publications.

Activities

When packing objects, it is not enough to pack them efficiently. Objects must be packed correctly. For instance, heavy objects must not be piled on top of fragile ones. Boxes must not be left hanging partly unsupported, and so on. Any business that needs to pack something has regulations about how objects may and may not be packed. The problem is, such knowledge is typically written on paper, in natural language, and so difficult to access for computers.

The central activity of this work package is to come up with a way of encoding this knowledge in a form that a computer can process and use for optimisation, and that a human without a computer science degree can read, understand and edit. This way, not only can the computer come up with packing plans that are space efficient, but also guarantee that such plans obey the business packing regulations. Most people find it easier to understand or describe a complex design in small pieces than as a monolithic whole. Similarly, in computer science, there is a formalism for describing knowledge in small pieces: rules. So we decided to seek to define a rule-based formalism, or language, for business packing regulations. Moreover, it must be possible to transform knowledge expressed in our language into executable code for tasks like computing packing plans.

Initially, we aimed at defining a rule-based language specifically for modelling packing problems. Later, we realised that limiting the scope to packing was no advantage, and so we widened the scope to modelling general discrete optimisation problems. The resulting language was called Rules2CP, or Rules To Constraint Programming.

Rules2CP allows the definition of library modules. We defined such a module tailored to modelling packing problems and named it PKML. It provides a set of generic primitives for use in packing rules.

All optimisation software developed in the project is based on the constraint

```
container_loading_constraints(Items, ItemsReferences, Bin, BinSize, Dims) -->
        domains(Items, BinSize, Dims) and
        lexicographic(ItemsReferences, Dims) and
        non_overlapping(Items, Dims) and
        gravity(Items) and
        stack_oversize(Items, 10) and
        stack_support_area(Items, 100) and
        stack_weight_sum(Items) and
        weight_balancing(Items, Bin, 1, 10).

gravity(Items) -->
        forall(O1 in Items,
          origin(O1, 3) = 0 or
          exists(O2 in Items, O1:uid # O2:uid and on_top(O1, O2))).

stack_weight(Items) -->
        forall(O1 in  Items,
                forall(O2 in Items,
                        (O1:uid # O2:uid and above(O1, O2))
                        implies
                        lighter(O1, O2))).
```

Example of PKML rules defining container loading constraints, gravity and stacking rules.

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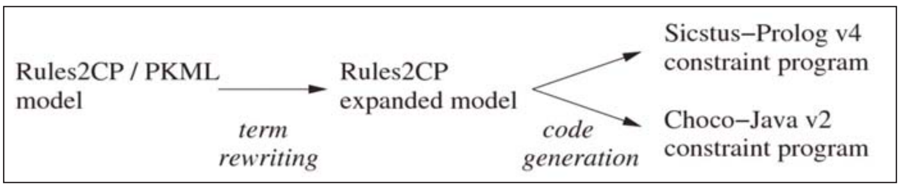
Julien Martin
(INRIA)

programming approach. The project uses two constraint programming platforms: the open-source Choco Java and the commercial SICStus Prolog platforms. A significant effort of this work package was the development of Rules2CP compilers: one compiler into Java for Choco, and another one into Prolog for SICStus.

At the same time, in collaboration with the Generic Placement Constraints team, we studied an alternative approach to compiling a subset of Rules2CP into side-constraints for the geost constraint, which is a computational workhorse in our optimisation software. The point is to achieve higher efficiency from a tight integration of multiple logical conditions in one single constraint.
Of course, Rules2CP was not carved in stone from the beginning. In particular, its facilities for describing search procedures evolved during the project, which required the corresponding parts of the compilers to be extended as well.

PKML models were developed for PSA study cases for pallet loading and container loading problems. The performance of the compiler and of the generated code were evaluated on PSA pallet loading and container loading test cases.
In order to firmly define the elements and syntax of Rules2CP, and to enable the encoding of packing models in XML, the de-facto universal interchange format, we also defined an XML DTD describing Rules2CP.
We started a new workshop series: Bin Packing and Placement Constraints (BPPC). The first meeting was held in conjunction with the CPAIOR'08 conference in Paris. Seven papers were presented there. The second meeting was held in conjunction with the CP'09 conference in Lisbon. Five papers were presented there. A third meeting is planned for the CPAIOR'10 conference in Bologna. Finally, the activities of this work package were reported in several peer-reviewed academic publications.



Compilation Scheme of Rules2CP/PKML

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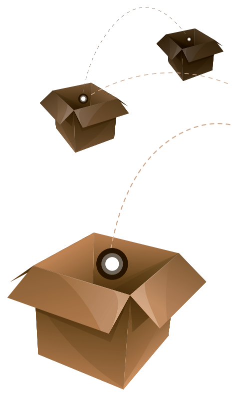
Research

Distributed Service-Oriented-Architecture in a WMS



In the scope of this research project Wide Scope led the work package dedicated to the integration of optimisation and visualisation tools. These require a highly dynamic Service Oriented Architecture (SOA) where information is supplied from a set of external systems into services in order to be displayed to several users, systems, graphical dispositions and environments.

The requirements also suggest that reusability, flexibility, usability and scalability are important considerations. The driver behind SOA is precisely the idea that technology should quickly adapt to rapid changes in the business landscape. In some respect, the "service oriented" aspect of SOA implies that technology is designed to serve end-users and business priorities, but also to be part of "building blocks" that compose a loosely coupled networked application.

Wide Scope implemented an SOA featuring an Enterprise Service Bus (ESB) as the aggregating and orchestrating element among optimisation solvers and visualisation tools and GUIs.

Objectives

The objectives of this work package dedicated to the integration of components in a common communication platform were:

- Design and implement a SOA based on Java EE technologies,
- Deploy the packing solvers as reusable services,
- Integrate the virtual reality tool as a consumer of the packing services.

Other parallel objectives in the scope of this IT work package included:

- Development of a PKML web-based editor,
- Deploy the Rules2CP business tool as a reusable service,
- Develop a GUI and solver for optimising Means-Of-Picking on an assembly line.

Activities

The activities carried out for achieving the proposed objectives required the collaboration of several partners and the results of several other work packages. They can be described under the following headings:

Implementation of an Enterprise Service Bus

At the heart of an SOA there is an ESB. It determines the heartbeat of the business services and through its veins flow the business logic and processes.
In the context of Net-WMS this concept is matched to the exposure of the several optimisation solvers and knowledge containers within a networked environment of warehouse management business processes.
Wide Scope deployed an implementation of the Open ESB tool.

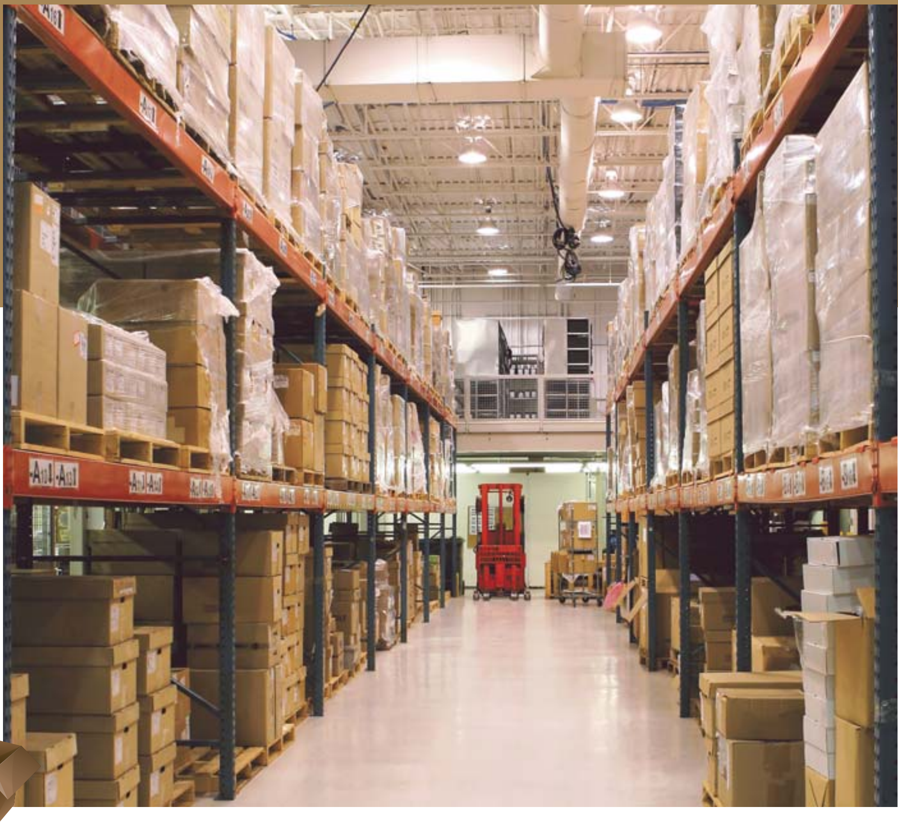
Integration of Net-WMS service producers

KLS OPTIM developed a set of packing solvers. These are Java libraries based on the constraint-programming tool Choco. These solvers expose an API that was wrapped by Wide Scope as a set of services exposed and deployed in the context of the common ESB.

On another hand, INRIA and ARMINES developed the Rules2CP tool that interprets a PKML program and produces a set of Choco or SICStus rules.
This tool itself exposes an API that was also wrapped by Wide Scope as a set of services published in the ESB.

Integration of Net-WMS service consumers

The Virtual Reality tool developed by CEA requires interaction with the packing solvers. This is achieved through the



WP leader:
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(Wide Scope)

Ana Pereira
(Wide Scope)

consumption of the corresponding service published in the ESB. This communication happens through Web Services since the packing solvers are developed in Java and the VR tool is developed in .NET.
The packing solvers are also consumed by another tool developed by KLS OPTIM that is a web-based GUI. This tool is a Java web application based on the MVC framework Struts whose presentation layer is a JavaScript Rich-Intranet-Application based on the ExtJS framework.
Wide Scope provided an integration of these tools with the packing solvers having the ESB to act as a "man-in-the-middle" of SOAP-based Web Services.

The picture below illustrates the ESB as the integration layer of these service producers and consumers.

Development of the PKML editor

Wide Scope developed a JavaScript PKML editor that can be embedded into any HTML page. This PKML editor interacts with the Rules2CP service published in the ESB and allows the creation and editing of PKML programs that produce a set of Choco or SICStus constraints.

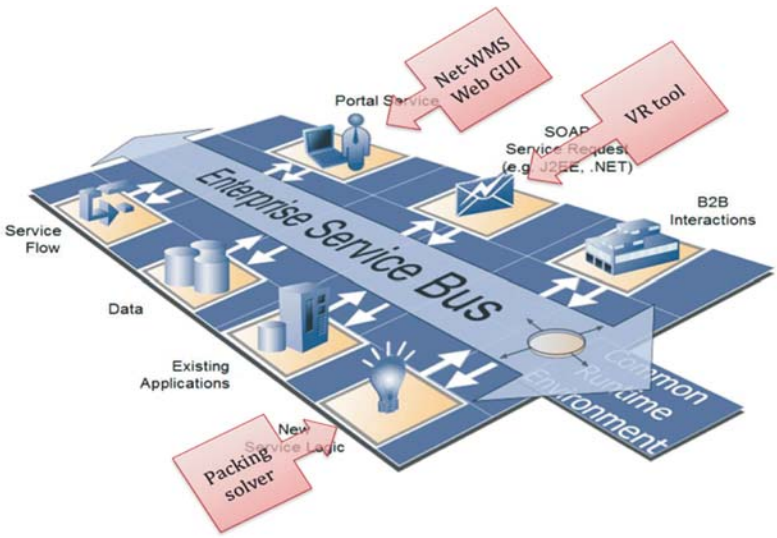
Development of the Means-Of-Picking optimisation solution

CRF provided a test case illustrating the problem of optimising the Means-Of-Picking, which consists of determining the allocation of operations and its required parts to stations in order to comply with a production cycle time while minimising the line-side storage used space.
SICS developed an optimisation solver based on SICStus Prolog and Wide Scope wrapped it into a web-based application for CRF to manage its data and solve its real test cases.

Results

This work package produced several important deliverables:

- An ESB implementation featuring the integration of solvers and GUIs required in the scope of several networked WMS test cases,
- A PKML web-based editor for the dynamic creation of packing rules,
- A web application for the planning of the Means-Of-Picking in an assembly line,
- A document describing the WMS networked environment developed, its architecture and its components.



Impact

Business Process Applications

This work package focused on the design and implementation of a business process application, which is a co-operative optimisation solver taking full advantage of corporate knowledge and of major optimisation technologies such as Constraint Programming, Mathematical Programming (MP) and heuristic techniques.

Objective

Our objective was to design models for packing items into containers, addressing requirements encountered in production, distribution and networked warehouses. The expected result was a set of parameterised packing solvers derived in different versions according to the structure and the type of packing to solve, yielding the following benefits:

- Reduce the cost of packing by a significant margin of 5 to 10%,
- Contribute to the competitiveness of the companies,
- Exploit the solution to cover sectors in logistics where such decision making solutions are missing.

Architectural design

The architecture design is J2EE compliant. Business classes to support the different modules: optimisation solvers, interactivity and mobility" The J2EE system architecture is built on top of basic features that any large business networked environment must consider. It is built from the ground up to be a service oriented architecture (SOA), i.e., it provides most of its business logic encapsulated as middleware services thus enabling third-party applications to be integrated. The chosen architecture enables the integration of optimisation components in 2-tier architectures (client-server) which are still dominant in the market.

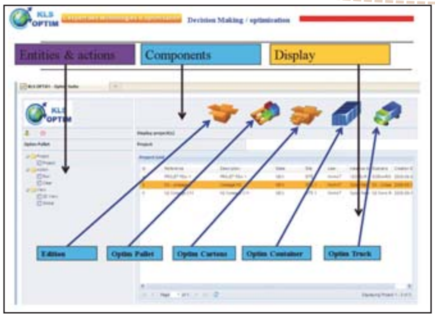
The work carried out in this work package was done in several steps:

- Architecture design and integration of tools. The aim was to use the best available J2EE technologies (Web 2.0, Ext JS, Struts, Java),
- Development of a prototype composed of optimisation and visualisation components based on the selected J2EE technologies,
- Development of API interfaces using SOA features providing efficient and secure Web Services,
- Development of generic and parameterised solvers and strategies for identified bin packing problems from the test cases.

Solvers (Optim Pallet, Optim Truck) developed by KLS OPTIM in the context of the Net-WMS project are based on the CP Choco (Java). Their design makes it possible to enrich their capabilities with additional external CP programs such as:

- Specific CP programs implementing an additional feature; e.g. if two products do not belong to the same group of orders they cannot be grouped in the same pallet. This feature can be activated or deactivated. The CP program is written by a CP specialist for efficiency reasons,
- CP programs generated by compilers; this is the case for PKML rules where each rule contributes to the knowledge data base. Rules are activated / deactivated by parameterisation.

The KLS OPTIM Solution



The solution is organised into a set of business packing components (modules) featuring capabilities that cover the complete process of packing including different functionalities: creating and editing scenarios, solving optimisation packing problems, visualisation of packing results, production of reporting. The solution is enriched with several API (XML, SOA) easing the interface with ERP and WMS packages on the market.

Optim Pallet

Optim Pallet is the optimisation component which serves as a basis for the different variants of optimisation engines developed in the work package. The figure above describes the different entities of a packing problem. In a warehouse:

- A bin describes a pallet,
- An item describes a carton; they correspond to products of orders,
- A model describes a proven packing configuration,
- A directive indicates the type of packing.

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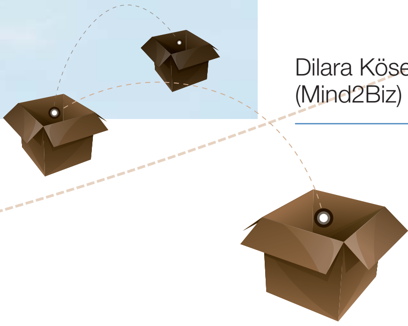


Optim Pallet optimises the number of pallets for a set of orders. A carton in a pallet may have up to six possible orientations which may increase the complexity in some cases.

Optim Pallet - Version Pallet Loading

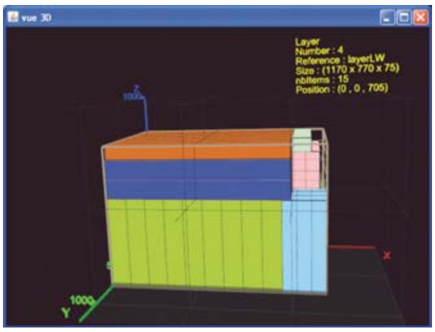
This business component is dedicated to designing optimal plans for loading products into cartons, boxes or pallets. The optimised plan is a single reference-pallet, all items are identical. The input parameters are:

- The dimension of the bin specified as length, width, height,
- The dimension of the item and its possible orientations,
- A set of solver directives.

The objective is to solve the problem by selecting the best arrangement of identical packs subject to business constraints:

- side up restriction, on a rectangular pallet,
- rotation restrictions (some 90° rotations are not allowed),
- height overlay (possibility to exceed the total height of the box within a limited length).

The component is powered by several variants of algorithms. According to the input parameters and to the solver directives, the business module selects the right algorithms.

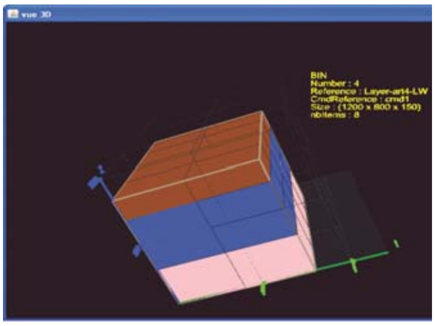


Optim Pallet – Single reference

This component is a typical solver required by OEM manufacturers, agro-food and medical industries and more generally speaking in many high volume production environments.

Optim Pallet - Version Pallet loading multiple references

This solver is a variant of "Optim Pallet – Version Pallet loading single layer". The pallet contains several references; the dimensions of the items (products) are not identical. The problem consists in packing boxes of various sizes into available pallets in a way which optimises the total number of pallets. This variant obeys a set of directives, the most important one of which is the packing by layers. The solver allows additional features like control of the layers, orientations, weight constraints, disposal of layers, etc.



Optim Pallet – packing by layers

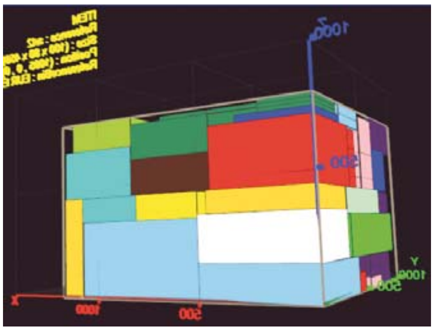
It is a typical solver required by the PSA applications, in production and distribution of compatible references.

Optim Pallet – Version multiple references – standard

This module is powered by a 3D solver which consists of packing boxes of various sizes into available pallets (larges boxes) in a way which optimises the total number of pallets. This requirement is the core of many problems which arise in distribution and logistics. A typical application is the preparation of orders in warehouses where one has to cope with many directives and constraints. The objective is always to minimise the total number of pallets.

- Planning of several orders,
- Capabilities to handle several types of pallets,

• Subject to orientation, fragility, stackability, weight/volume and constraints.



Optim Pallet – standard version – packing of cartons with different sizes.

Optim Truck / Vehicle

In a network of warehouses, transport can be an external activity handled by specialised transport companies. Through EDI or Web Services, warehouses inform transporters of the number of pallets to deliver to customers, with or without the appropriate parameters. This module proposes an optimal loading plan for each vehicle of the fleet company. The solver is tuned to handle specific requirements encountered in the optimisation of vehicle loading plans. Constraints are classified mainly in two classes as described below.

Class A: feasibility constraints

Pallets and their logistical attributes are known. The same holds for the vehicle. In addition, pallets which are assigned to a vehicle are also input parameters. The objective is then to check the feasibility of a load whilst respecting a set of constraints.

• Vehicle constraints: Maximum weight and Volume constraint,
• Block constraint: pallets are grouped into piles or layers. There are many constraints attached to blocks like the stackability constraint,
• Priority: orders are grouped and are given priorities,
• Delivery orders: this constraint determines the order in which clients are visited.

Class B: Quality solution

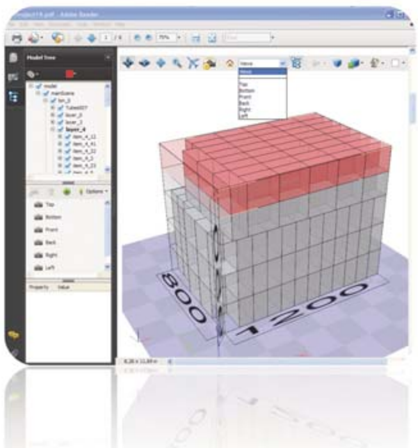
• Preference: a soft constraint that contributes to the quality of a solution,
• Worth constraint: this constraint is encountered in the PSA test case. Packed products for export do not have the same worth value. All worth products must be packed in the front of the truck to minimise risk.

For a given class of problems, the solvers of Optim Pallet improve the current packing by a good factor ranging **between 5 and 15%** depending on the packs, business constraints and objectives.

Net-WMS Reporting Module

In industrial environments, loading plans are mostly drawn and visualised with the help of views of placement whereas the views in the loading reports are attached with detailed tables. These extensive tables describe additional information that helps understanding the loading plans. The data presented on the tables are mostly originating from database applications, but also contain written forms of instructions. The most viable views used are top, side and front views of the whole containing object and, where applicable, of layers within the containing object. For the reporting activity, users mostly exploit environments such as Microsoft Office applications and feed the drawings manually with detailed instructions and tables of information.
It has been observed that this reporting task is a highly time-consuming activity. It is also remarkable that some industrial cases point out that end-users require additional means to accompany/replace the views with detailed instructions so as to better and correctly understand the sequence of loading, especially for those sections which are not visible from outer-views. Current practices show that in such cases real-photos and 3D drawings are exploited. But making a 3D drawing requires professional CAD applications which can only be utilised by CAD-specialists. Hence the reporting cannot be carried out by a regular logistics expert.

For these reasons, the consortium decided to investigate reporting features which will automate the reporting activity but will also support 3D visualisation. The objectives have been defined as to minimise 1) time and effort 2) technical drawing expertise required to generate loading plan reports, but also 3) provide a flexible environment where different customers can impose their template for report structure.
In line with these objectives, Mind2Biz has developed a reporting module which exploits advanced 3D visualisation facilities. Among available formats, PDF has been chosen for its support for 3D components, features like compression, portability, free-support of viewers, annotation facilities and broad acceptance of usage. The portable PDF report generated automatically is of very small size and provides an interactive "GUI" alternative for visualising the packing layout determined by the solver (OptimPallet). The user with 3D visualisation capabilities can interact with the loading on the pallets, the layers and its components. With mouse clicks, the user can rotate the 3D components, explore its hierarchical components, change settings such as rendering, colours, angles of views etc, can benefit from pre-defined views. It is under user-control to print the desired scene displayed on the screen. In terms of flexible report design, the visual characteristics of the report and the decomposition of its design can be parameterised by XML/HTML cofiguration files. Hence the module provides users the capability to customise the structure of the report with respect to their requirements.



Impact

Industrial Applications, Validation and Evaluation

WP leader:
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(CRF)

The role of this work package was to ensure the relevance of the Net-WMS prototypes to the reality of industry business cases and to evaluate the results achieved. As assessed by the end users, the prototypes do solve some of the critical issues they face in the logistic process such as Packing, Pallet loading, Container loading, Assembly line load balancing, and space constraints.

Prototypes were developed to propose solutions to heterogeneous test cases provided by our three industrial partners: PSA Peugeot Citroën (PSA), Fiat Research Centre (CRF) and KLS OPTIM (KLS). When applied to real company business cases, the power of the Net-WMS tools in solving packing problems, organisation of plant internal areas, palletisation and vehicle loading has been clearly demonstrated.

The solutions developed for each scenario had to feature common benefits and enable end-users to:

- solve the proposed problems with automatic tools while they were traditionally tackled in a manual way,
- find global solutions in which all constraints are considered, instead of using different local optimisation approaches.

Objectives

Among the many wide-ranging benefits expected from the Net-WMS project outcomes, those have been clearly identified upfront as goals to reach by the end of the EC-funded period and have been used as criteria when assessing the relevance and quality of the Net-WMS prototypes:

- Minimise space occupation in the warehouses, preparation areas, line-side storage,
- Balance the assembly line workload while respecting the space constraints,
- Assure an ergonomic working environment for the assembly workers, where each part is delivered exactly where it will be needed,
- Optimise the volumes of CKD packing sent to the assemblers,
- Find optimal solution faster, improving on today's manual approach,
- Customise solution provided by the solver via iterative simulations,
- Design new optimal conditioning and packaging plans for small and large series in production for existing and new products,
- Automate the optimisation of the pallets' loading plans in distribution,
- Reduce the amount of material packing thus contributing to eco-efficiency and competitiveness,
- Contribute to the quality of packing in production, distribution and transportation, thus easing the work of the operator during picking, preparation (packing and assembling) and loading phases.

Applications

CRF decided to apply the system proposed by Net-WMS to its core process: the assembly line production. Since modern factories have to increase the reconfiguration frequency of their plant internal areas in order to quickly face the variability of market requirements and to survive in the current competitive environment, CRF selected two important test cases:

CRF assembly line test case

- Optimisation of line-side storage re-design (providing the right components to the right station at the right moment, minimising space occupation in internal areas, assuring an ergonomic working environment for the assembly workers, etc.),
- Optimisation of preparation area configuration (layout, container location, etc.) by means of virtual reality simulation.

PSA selected several test cases relevant to its CKD process:

- Optimisation of packing cartons on pallets,
- Optimisation of packing pallets in containers,
- Optimisation of complete loading (from cartons to containers),
- Manual validation and customisation of packing solutions provided by the solvers featuring Virtual Reality interfaces.

KLS OPTIM worked on four test cases highlighting the different classes and variants of problems with their respective constraints and objectives. The problems were taken from different sectors in logistics:

- Optimisation of loading plans in production,
- Optimisation of loading plans in distribution,
- Optimisation of vehicle loading plans in distribution,
- Optimisation of container loading for export in wine industry.

Results

As the project comes to its conclusion, the Net-WMS end-users are satisfied that their objectives have been met, the best proof being the early adoption of several optimisation components in their respective production environments.

In summary and from a user point of view, the most important and useful results achieved by Net-WMS after forty months of collaborative work are the capability to:

- Support the interactive re-design of plant internal area and line-side storage via the interaction of the human expert and the automated solver,
- Support the evaluation, verification, and comparison of multiple designs,
- Provide visualisation of possible results in order to highlight weak points and to propose necessary recovery actions
- Optimise time to conceive and optimise the conditioning and the packing of CKD; solutions provided by Net-WMS are not necessarily better than manual solutions provided by packing experts, but they are calculated in a much faster way,
- Provide a Standalone Virtual Reality Module to explore & manually modify a packing solution produced by the solver,
- Provide a complete J2EE innovative solution for packing in the logistical sector of production,
- Provide a complete J2EE innovative solution for packing in the sector of distribution for networked warehouses,
- Convince the end-users to integrate a set of resulting modules in their production environments, thereby demonstrating that the exploitation of the project results had already started.

Impact

Dissemination and Exploitation

WP leader:
Philippe Rohou
(ERCIM)

By working on real-size industrial problems taking into account all business requirements, the Net-WMS project has advanced the state-of-the-art in bin packing, in constraint programming and in modelling languages, going far in the technological transfer toward the end-users.

Not all problems have been solved but we can draw the following conclusions:

- The optimisation technology developed around the geometrical constraint kernel geost coupled with suitable search strategies does have the capability to solve real-size industrial packing problems, ranging from pallet loading and container loading to assembly line load balancing under space constraints,
- There are some hard instances however, especially in pallet loading problems, for which the automatic placement finds sub-optimal solutions, not as good as expert solutions, and we are not aware of alternative automatic methods to solve these problems optimally,
- 3D visualisation and virtual reality provide valuable tools to improve solutions and refine them taking into account human factors and feasibility constraints that are difficult to formalise
- The Packing Knowledge Modelling Language PKML does provide a high-level and flexible language to express industrial requirements and compile them in efficient constraint solvers,
- The Service Oriented Architecture and J2EE components discipline ease the deployment of various components on different machines and ensure their interoperability in a cost-effective manner.

These results have been disseminated to the scientific community through several peer-reviewed publications and the organisation of dedicated workshops associated to the major conferences of the field. Our consortium of European researchers has been informally enlarged on the theme of constraint-based optimisation for packing and will continue investigating this topic, with the aim of contributing for instance to better search strategies for higher-dimensional bin packing problems with rotations, and to the handling of complex (non-rectangular) shapes.

The technological transfer of Net-WMS components is already ensured through their industrialisation by KLS OPTIM, and through their integration in the open-source libraries or in the commercial software of the academic partners. Systematic promotion of the project results in industrial circles has been done in the last three years via strong presence in the specialised tradeshows. The KLS Optimisation Suite has been released in a first version, putting Net-WMS technology on the shelf for the market at the end of the project, but also positioning Net-WMS at the beginning of a new generation of agile supply chain management systems.

http://net-wms.ercim.eu/

NET WMS

Networked Businesses in WMS

Final Project Report

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