5th International Conference from Scientific Computing to Computational Engineering
5th IC-SCCE
Athens, 4-7 July, 2012

TOWARDS A HOLISTIC OPTIMIZATION OF PRODUCTION SUSTAINABILITY: A MULTI-LEVEL APPROACH

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Keywords: Sustainability, optimization, production process, product life cycle, life cycle assessment

Abstract. *Long-term environmental sustainability requires that artifacts, materials, systems and processes be designed to minimize energy and waste and to maximize reuse and utility. The sustainability Optimization task is typically an attempt to compromise conflicting goals, such as: Minimize negative impact on environment, maximize quality, minimize cost, maximize profit, minimize time, etc. In addition, a holistic view of sustainability must cover the entire life of a product from material procurement, design, production, distribution, usage, up to its end-of-life. Each of these stages contains a number of sub-stages and more detailed levels. The distribution stage may include sub-stages as packaging and transportation, while the production stage may go down to the shop floor and machine tool detail levels. Between the various stages and objectives, there is usually some kind of (contradictive) relations or mutual influences that may be complicated and not always obvious. As a result a holistic sustainability optimization for the entire product life cycle is not a trivial task and most sustainability solutions today focus only on a part of the entire cycle, e.g., scheduling, production or recycling, etc. In this work, a multi-level approach is proposed that distributes the product information per stage and level, resolves locally the sustainability issues and consolidates the results to the upper level for a holistic view of the production sustainability performance. The proposed framework architecture will be subsequently applied to a series of test cases, each focusing at a different stage/level of the production life cycle to demonstrate both local and holistic capabilities of the approach.*

INTRODUCTION

Sustainability Optimization

The optimization problem of production process planning, scheduling and rescheduling received increasing attention the last decade. A process plan links design and manufacturing. A typical process plan specifies raw materials, components, processes and operations necessary to create the final product. It contains information on manufacturing processes, their parameters, the machines, and the tools required. Several possible process plans may be generated due to the availability of alternative processes, schedules, machines and tool parameters for creating the same part or product.

Long-term environmental and societal sustainability requires that artifacts, materials, systems and processes be designed to minimize energy and waste and to maximize reuse and utility. The sustainability Optimization task is typically an attempt to compromise conflicting goals. In any manufacturing process there are many objectives that are subject to optimization, such as: Minimize negative impact on environment, maximize quality, minimize cost, maximize profit, minimize time, etc. Between these objectives there is usually some kind of (contradictive) relations or mutual influences that may be complicated and not always obvious. This inherent complexity leads to a number of objective functions that need to be minimized (some) and maximized (others) at the same time, i.e. globally optimized. These cases constitute the so-called Multi-Objective Optimization (MOO) or poly-optimization problems [1].

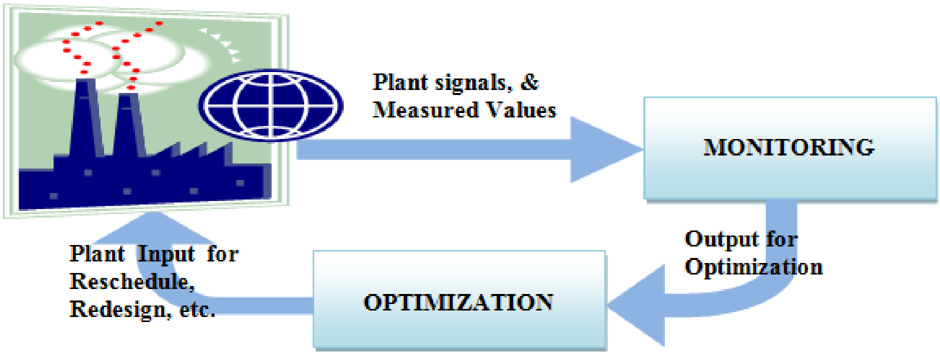

Figure 1: Plant Optimization

Optimization Methods

A large number of Multi-Objective Optimization approaches can be found in the literature and among them we can favor the: weighted objectives method, hierarchical optimization method, global criterion method, distance function method and minimum-maximum, goal programming method, and finally the evolutionary algorithms (Fig. 2) [O1, O2].

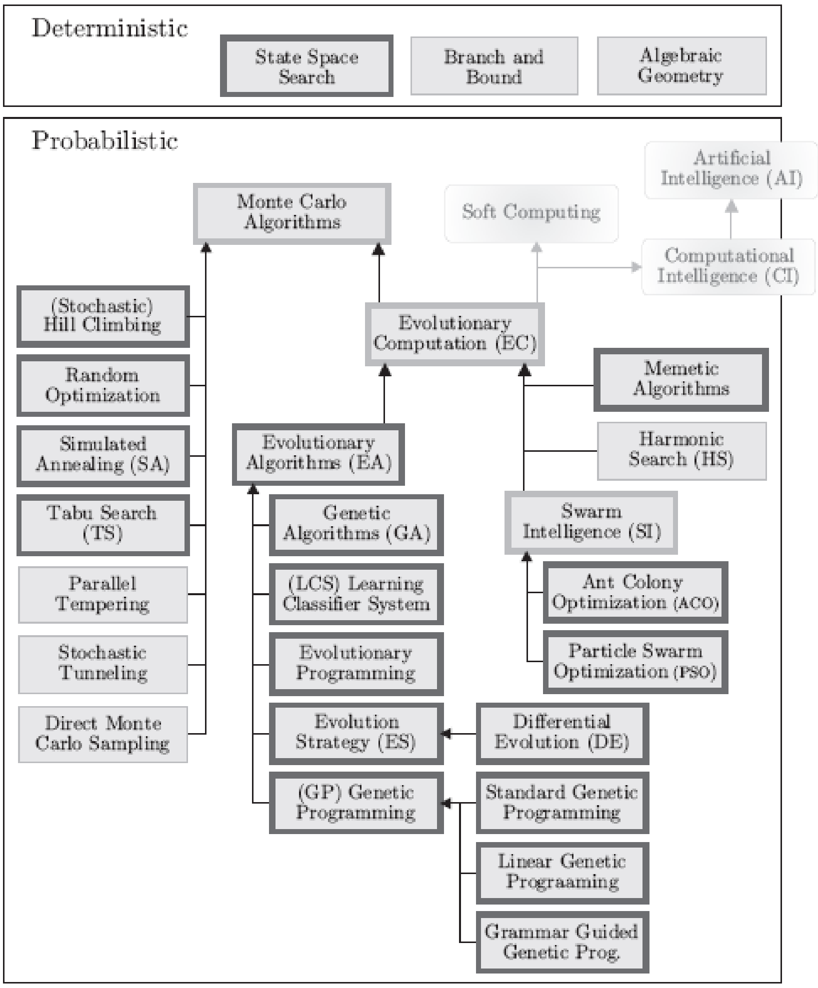

Figure 2: Global Optimization Algorithms

From the approaches mentioned above, the Evolutionary Search Algorithms have been shown to be more efficient and robust for large-scale complex problems. They consist of three main classes: evolutionary programming, evolutionary strategies and Genetic Algorithms (GA). The Genetic Algorithms have been successfully applied by the scientific community on several aspects of process optimization [3, 4]. The issue of finding an optimal plan, from the viewpoint of combinatorial optimization, is known to be NP-hard, therefore, evolutionary techniques and GAs receive particular attention [5, 6]. GAs can handle large populations of candidates and converge to the best individuals avoiding the combinatorial problem. The existing studies have indicated that GA can be used as a very effective search technique in solving difficult problems because of its ability to move from one solution set to another and flexibility to incorporate the problem specific characteristics.

Sustainability Models

The introduction of sustainability issues complicates the already complex problem of process optimization by adding more objectives to meet, beyond the typical ones (quality, time, utilization, etc.). The Manufacturing Sustainability Optimization is by its definition a Multi-Objective Optimization (MOO) problem. It incorporates a large number of sustainability methods, goals, targets, indexes, indicators or metrics and product properties that need to be optimized, by adjusting a large number of product/process/tool parameters, thus leading to a large number of alternative solutions. These Sustainability Targets, Indicators & Methods are elements of the Sustainability criteria and objective functions that an optimization tool will try to meet or optimize respectively. Targets should be defined based on the sustainability and performance goals or requirements.

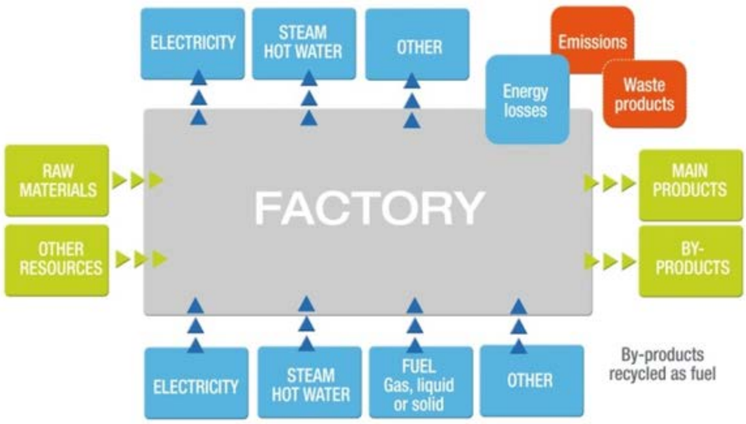

Figure 3: Factory I/O related to sustainability

The targeted quantities are reported by the corresponding indicators. Indicators should meet or try to approach their targets. The optimization is driven by the Indicator-Target difference that should be minimized or optimized. Often, multiple indicators aggregate to an overall sustainability index. The indicators used by the optimization are usually composite values from various Measured Values monitored from the process or plant.

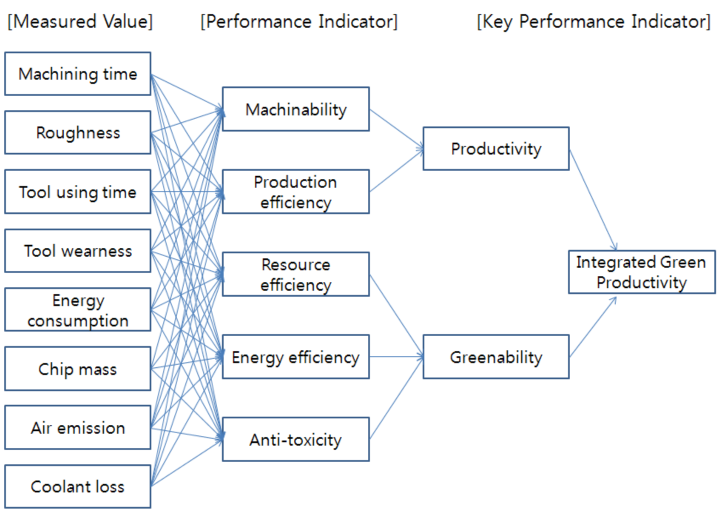

Figure 4: Example of aggregation of measured values (MVs) to performance indicators (PIs) and to a KPI

Sometimes composite indicators may send misleading, non-robust policy messages if they are poorly constructed or misinterpreted. Sub-indicators should be selected meticulously. Choice of model, weighting mechanism and treatment of missing value also play a predominant role while construction of framework. Number and nature of the components that will make up part of the composite index need to be determined based on theory, empirical analysis, pragmatism or intuitive appeal, or some combination thereof. Other important selection criteria include validity, reliability, comparability, simplicity, and data availability. Selection requires a balance between simplification and complication.

THE MULTI-LEVEL APPROACH

In order to optimize the performance of the manufacturing process, a more complex model of the process is required. This enhanced process & sustainability model should be able to calculate the production performance on sustainability, as well as, the production performance regarding time, cost, quality or any other indicator of interest. In addition, it should handle the different sustainability optimization issues at each stage and layer, to satisfy the different needs and points of view. A general sustainability optimization for the entire life cycle of the product is not the same as the sustainability optimization of a machine tool stage, although they are related to each other.

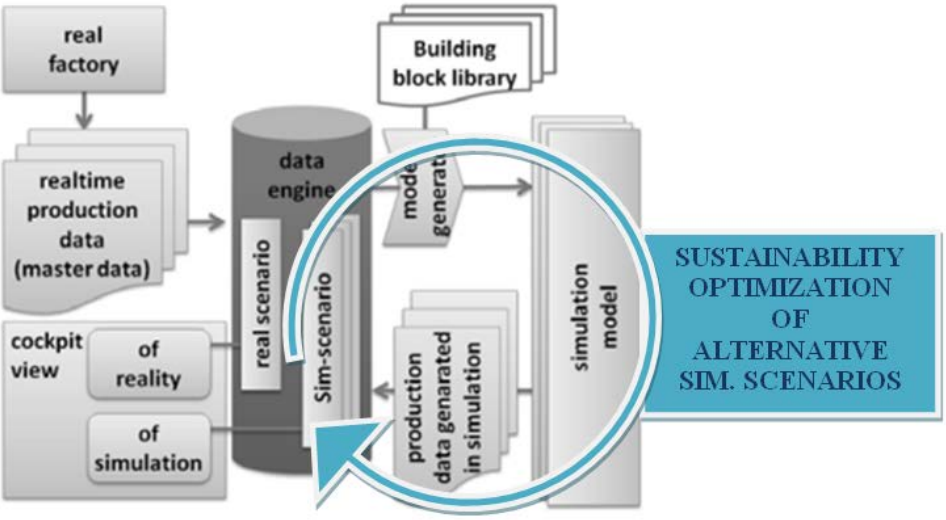

Figure 5: A Planning Information Model from [O12] and the role a Sustainability Optimization tool.

The Sustainability Optimization involves many metrics & indicators and constitutes a multiple-objective optimization problem. Even if overall indices are used the objectives are still many and contradicting. The basic methodology is described in the following steps:

- Index & Indicator targets/goals will provide objective functions for the optimization problem and the optimization tool will try to reduce the overall target-indicator distance based on the adopted sustainability methodology.
- The optimization Search Space is composed by all potential changes of the configuration proposal elements (materials, process sequence, tools, operational parameters, recycling, etc.). Acceptable combinations of the Search Space elements will populate the optimization Problem Space as they will be defined in the corresponding models.
- The optimization Problem Space, is the space of possible solution candidates, composed of all potential product/process/tool configuration alternatives. Sustainability Methods & Indicator functions are applied to the Search Space elements in order to assign the corresponding sustainability index/indicator.
- The evolutionary optimization tool iteratively selects the best elements according to the objective functions and finally delivers the best solution.

Due to this complexity there is not yet available a complete holistic model and method or approach to handle this problem as a whole. Instead, many successful solutions can be found in the literature that focus and solve a sustainability issue regarding: material selection, transportation, scheduling, tool operation, production, packaging, product use, recycling, or other horizontal or vertical layers/stages of the overall process.

In this work we consider the synthesis of various local solutions towards a holistic optimization method. The multi-level method handles the entire production model as a set of interconnected levels, each having its appropriate optimization method. In the following section we present the proposed architecture for a general manufacturing process.

Product Life Cycle Model

Holistic sustainability must cover the entire life cycle of a product e.g. from design to recycle. The life of a product is divided in several stages such as: design, raw material procurement, production, product distribution, usage and end-of-life (Fig. 6). Optimizing each stage separately can be much simpler but may also overlook stage interdependencies. For instance the selection of the raw material affects the sustainability indices at the production stage as well as at the procurement and end-of-life (recycling) stages, raw material transportation may be related to the finish product distribution stage, and the product design relates to the sustainability values during its useful life.

A product life cycle model should depict the various stages with their parameters, sustainability indices and their interdependencies. Holistic optimization is based on this model to relate interdependent layers of different stages.

Figure 6: Stages in a product life cycle model

Production Stage Models

Each stage at a product’s life is usually a different and separate engineering problem that requires different solutions for sustainability. Some of these stages may contain many & complex layers that require completely different approaches and other stages may be more trivial. A production stage model connects the various sub-stages and layers of a stage to the overall product life cycle model to exchange parameters and indices.

For example, in the above model the various stages may contain many layers related to each other and to other stages (Fig. 7). E.g.: the Procurement stage has the material sources and material transport layers that relate to each other but they also can be optimized either separately or in combination with the product distribution stage that also contains packaging (packaging material) and transportation layers for the completed product. Other stages can be more complicated. The Production stage has several sub-stages such as, planning, scheduling and execution, and each sub-stage has several layers e.g., manufacturing process, machine-tool, cut path, etc. Each layer has its own sustainability and optimization goals and techniques.

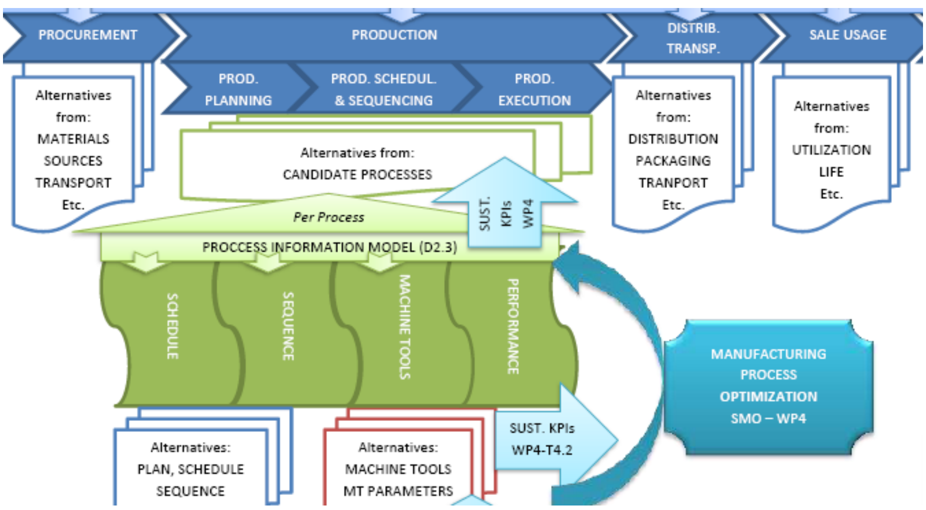

Figure 7: Sub-stages and layers in a product life cycle model

HOLISTIC SUSTAINABILITY OPTIMIZATION

Stage-Level Optimization

At a higher level, sustainability optimization can be applied for an entire stage such as, Material optimization, Design optimization, Manufacturing optimization, Transport/Packaging optimization, Recycling/Reusing optimization. For less complex procedures and stages this can be seen as one task but for the more complex stages such as Production, there may be more optimization layers.

Sub-Stage Level Optimization

At the Production stage, optimization can be applied at the Manufacturing Process level to select the move/cut/drill sequence, or, at the machine tool level to optimize its utilization, or even down to the cut-path level to select an optimal path for a specific operation (Fig. 8). Each sub-stage may have a local Machine-Tool model or Machining-Process model the can be used for locally optimize the sustainability of this level. These local models connect to the above production stage model in order to exchange parameters and indices.

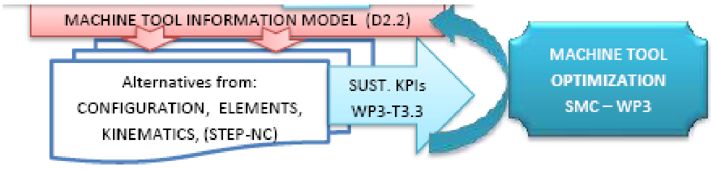

Figure 8: Sub-stages and layers in a product life cycle model

The Holistic Multi-Level Approach

A holistic process optimization for sustainability must take in to account all the aforementioned models and levels of optimization into one framework (Fig. 9). The holistic optimization tool must be able to contact each stage and sub-stage model, retrieve their parameters and the corresponding sustainability indices, and, drill down to the lower layers when required in order to update the local sustainability optimization results.

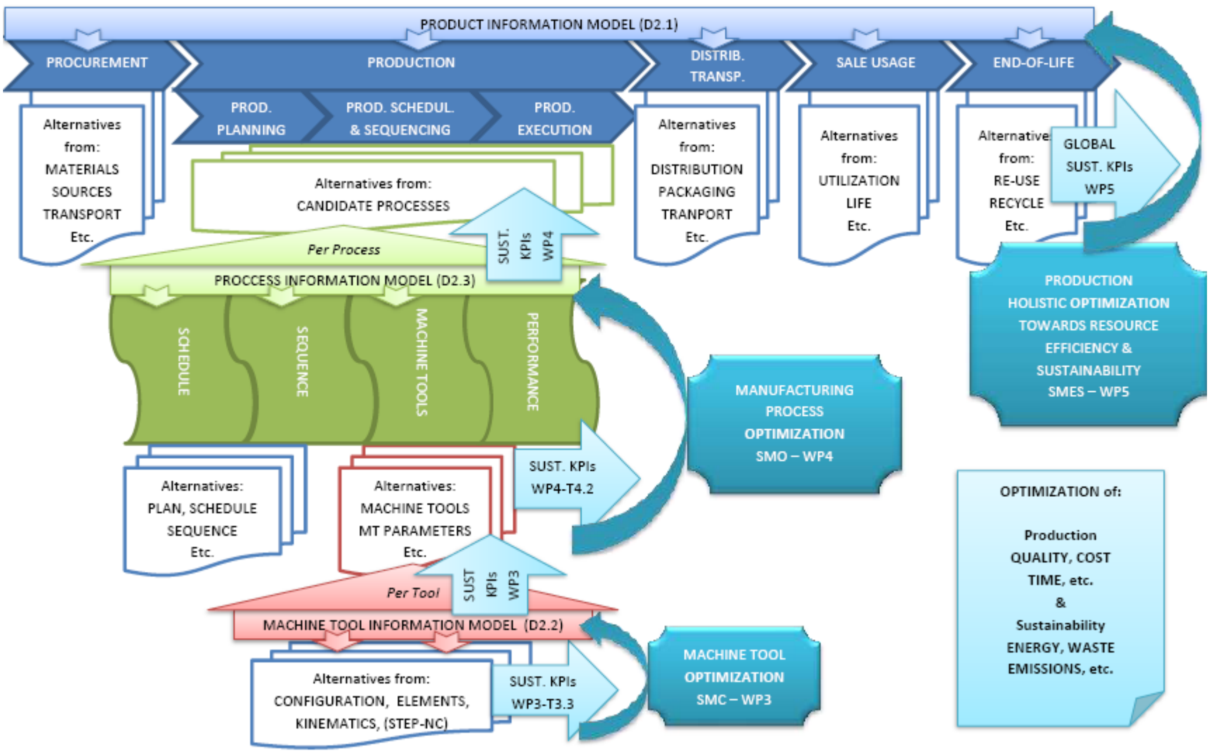

Figure 9: The holistic approach

In order to achieve this performance an advanced infrastructure framework for information storage & communication is required.

Implementation Framework

The holistic sustainability optimization will be supported by a framework that supports information exchange at all production stages and levels through a common Manufacturing Information Pipeline (MIP) (Fig. 10). All collaborating tools and applications at all levels will exchange information through the MIP and through the corresponding databases.

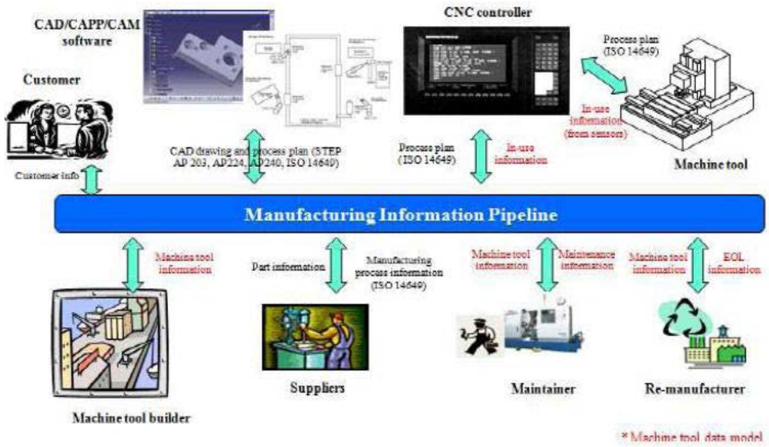

Figure 10: The Manufacturing Information Pipeline

The databases and the applications can be either centralized or distributed (Fig. 11). The optimization tool by using the MIP will be able to retrieve stored information, request new data or run simulations in order to define and compare the sustainability indices that correspond to each candidate alternative realization of the product life-cycle model.

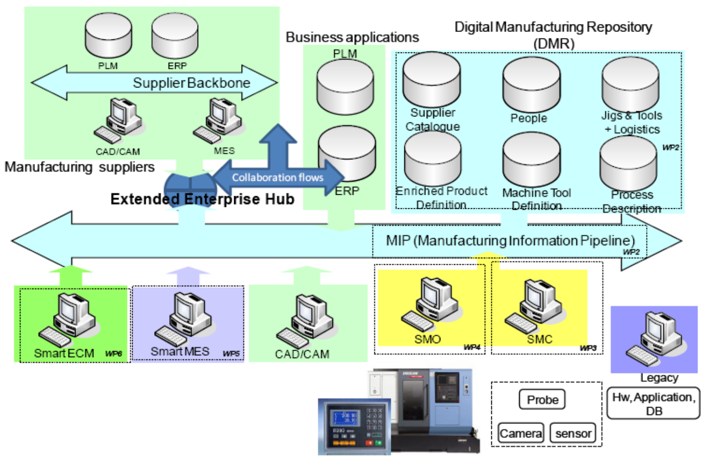

Figure 11: The Distributed Framework

CONCLUSIONS

In this work, the concept of a holistic multi-level sustainability optimization approach is proposed that distributes the product information per stage and level, resolves locally the sustainability issues and consolidates the results to the upper level for a holistic view of the production sustainability performance. The proposed architecture will be subsequently applied to a series of test cases, each focusing at a different stage/level of the production life cycle to demonstrate both local and holistic capabilities of the approach.

ACKNOWLEDGMENTS

The work presented in this paper has been performed under the EU-funded R&D project FOFDATION with contract number FP7-ICT-2010.10.1-260137

REFERENCES

[1] Michalewicz Z., (1996) *Genetic Algorithms + Data Structures = Evolution Programs*. Springer-Verlag, 1996, New York.

[2] Fonceca C., Fleming P. (1995) "An overview of evolutionary algorithms in multi-objective optimization". Evolutionary Computation 3 (1995) 1-16.

[3] Weise Thomas, (2009), *Global Optimization Algorithms - Theory and Application*. Newest Version: http://www.it-weise.de, 2009-06-26.

[4] Shu Q., Gong G., Wang J., (2010) "STEP-NC Based Machining Sequencing Using Genetic Algorithm". *Chinese Control and Decision Conference*, 2010, IEEE.

[5] Bierwirth Christian, Mattfeld Dirk C. (1999), "Production Scheduling and Rescheduling with Genetic Algorithms". MIT, Evolutionary Computation 7(1): 1-17, 1999.

[6] Lee H. and Kim S.-S. (2001), "Integration of Process Planning and Scheduling Using Simulation Based Genetic Algorithms". Int J Adv Manuf Technol 18:586–590, 2001.