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DEVELOPMENT OF A SMART SUSTAINABILITY OPTIMIZER (SSO) ALGORITHM FOR COMPLEX MANUFACTURING ENVIRONMENTS SUCH AS FACTORY WORKSHOPS

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Abstract. *In this paper the concept of the Smart Sustainability Optimization (SSO) is presented; a specialized optimization tool for manufacturing environments. The role of the SSO is to form an integral part of a Manufacturing Execution System and interact with other subsystems (conventional scheduler) or tools (PLM, ERP) in order to provide improved and optimal production schedules from the sustainability point of view and make the process “smart”. The SSO tool may not only optimize the production at the planning/scheduling level; it may also interface other optimization levels towards a global sustainability optimization of a product. It selects the optimal production schedule based on available schedules, sustainability evaluations, time & cost information and any product LCA & ERP inputs needed, while working on-line using the current information and can be invoked whenever a new schedule or re-schedule is required. The test use case is a factory shop floor with up to 30 machine tools that should be optimized for sustainability in production (e.g. energy, social and emissions key performance indicators).*

1 INTRODUCTION

Sustainability in general

Sustainability, or sustainable development, was defined by the World Commission on Environment and Development (also known as the Brundtland Commission), as development that “meets the needs of the present without compromising the ability of future generations to meet their own needs.” [1].

Sustainability, in general, can be defined as humanity’s investment in a system of living, projected to be viable on an ongoing basis that provides quality of life for all individuals of sentient species and preserves natural ecosystems. Sustainability in its simplest form describes a characteristic of a process or state that can be maintained at a certain level indefinitely. In the past, complex human societies have died out, sometimes as a result of their own growth-associated impacts on ecological support systems. The implication is that modern industrial society, which continues to grow in scale and complexity, will also collapse.

The term, in its environmental usage, refers to the potential longevity of vital human ecological support systems, such as the planet's climatic system, systems of agriculture, industry, forestry, fisheries, and the systems on which they depend. In recent years, public discourse has led to a use of "sustainability" in reference to how long human ecological systems can be expected to be usefully productive.

The evolution of the concept of Sustainability in engineering design is modern, where it is a fundamental change in philosophy, it is a nonlinear process driven by internal values instead of compliance in response to imposed requirements. This requires a multi-disciplinary approach to decision making and consideration of long term sustainability over short-term benefits [2].

2 SUSTAINABILITY OPTIMIZATION

Sustainability and its optimization in the FoFdation project

The SSO is being developed as part of EC project "Foundation for the Factory of the Future – FoFdation)" [4]. The FoFdation project aims to enable the Smart Factory integration towards real-time networking and adaptive capability, which among other things envisions:

- Supporting an advanced Manufacturing Execution System (MES) providing not only integrated process automation but also extension of its scope to achieve energy efficiency and sustainability goals as well as waste reduction and e-manufacturing.
- Reducing product integration, time-to-market costs and resource diagnosis-maintenance costs through a common control and monitoring platform.

Specifically, a new generation of MES is being developed for supervising productivity and sustainability indicators to meet the triple-bottom line corporate objectives. This concept proposes an extension of MES towards sustainability monitoring and control. Today, the sustainability strategy of many manufacturing companies focuses on the Triple Bottom Line integrating economic, environmental and social goals. In order to give a holistic vision of the manufacturing operations in a company production-to-enterprise, integration including extension to sustainability control will be achieved.

The FoFdation project proposes a straightforward approach for achieving sustainability goals: by leveraging an existing MES functionality to manage raw materials and resources. Moreover, the act of automating a manufacturing process to increase efficiency reduces cycle times, reduces human error and potential re-work, increases visibility of material flow and optimizes scheduling – all driven by economics. At the same time, these changes reduce energy expenditures, reduce labor – by reducing the use of gasoline consumption and capital expenditures such as office space and the energy required to power and heat them – and minimize scrap material, all facets of environmental stewardship.

The data from these automation efforts has been traditionally used to make decisions on what to produce and when to produce it. But that data can also be used to make further cost reduction decisions, such as shifting production schedules to accommodate running in off-peak hours and potentially selling surplus energy back to the grid, forwarding the latest trend: corporate responsibility through the right decision supported by an overall dashboard for Smart Factory Integration. This new generation of MES developed in the project incorporates several dedicated modules to address the above objectives and requirements. This enhanced MES (or Smart MES) will be able to optimize its traditional results for sustainability, such as scheduling and others, and showcase this ability for applications areas such as Automotive and Aerospace [5]. The concept of SSO integration with MES is shown below in figure 1.

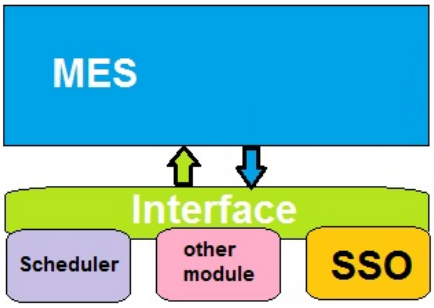


Figure 1 – the SSO within the MES

This optimization for sustainability takes into account multiple objectives and constraints of varying levels that are quantitative (e.g. manufacturing cost, energy consumption, waste management, etc.) and qualitative (e.g. environmental friendliness, personnel health, operational safety, etc.) in nature.

The Smart Sustainability Optimizer is a software tool currently under development by Paragon from scratch for application to a generalized manufacturing example of an automotive plant shop floor consisting of 8 operation points (OPs) and 30 machines (figure 3). Its focus lays on the total sustainability in production (energy, social, emissions, etc.) for:

- Optimized scheduling: i.e. producing optimized work-order schedules for the Smart MES.
- Optimized machine operation definition: further to the direct Sustainability Approach on fixed Shop Floor machine configuration, the next step towards optimized sustainable production is to consider the potential for dynamic flexibility, for example to reassess the number of active machines per operations

group and/or to reassign certain machines to Operation Groups other than those initially assigned to, depending on the number, type and deadlines of work-orders. The SSO will also focus on handling unforeseen problems such as bottlenecks due to machine breakdown, etc.

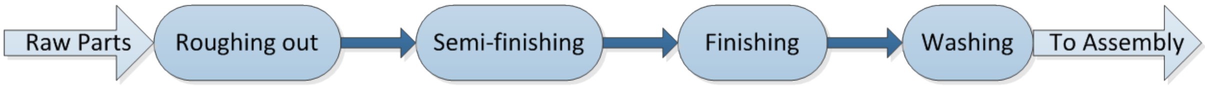


Figure 2 - Simplified example UC with three OP/machines

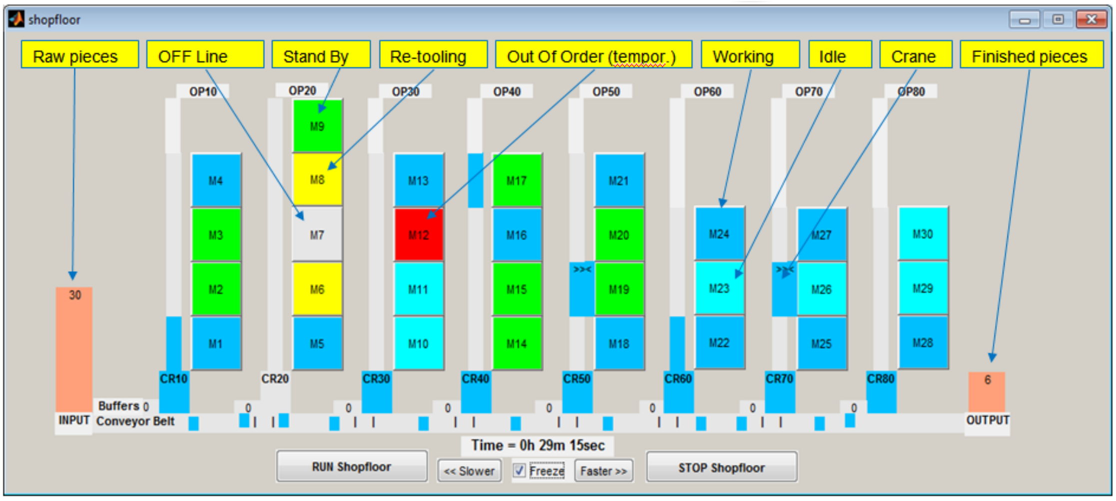


Figure 3 – A full generalized example with 8 OPs and 30 Machines

3 SMART SUSTAINABILITY OPTIMIZATION (SSO)

In order to enable the broad spectrum of operation of the SSO, a front-end GUI will be developed as part of a general control and viewing Dashboard, for accepting the necessary inputs either automatically or through human interaction and for displaying results for approval by the administrator.

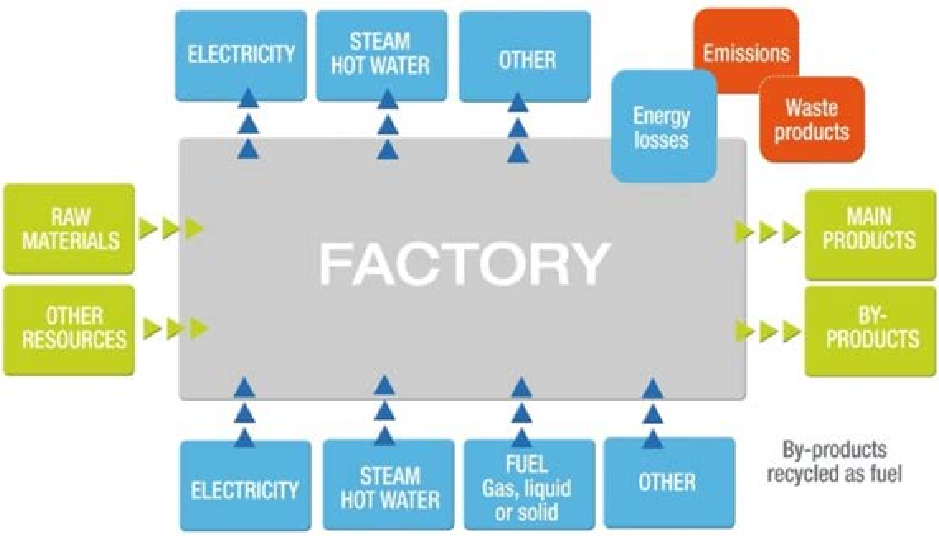


Figure 4: Factory I/O related to sustainability

The SSO is being developed using Evolutionary Optimization Algorithms, as the problem it is addressing is NP-hard [6, 7]. It is being developed to request and accept all relevant inputs regarding scheduling and sustainability metrics via Interface from the MES or any other relevant source, depending on the system organization implemented. For inputs that are not available automatically from within the system, the SSO will be able to accept them via the front-end GUI or to mark them as non-available. In the latter case, the SSO will operate based on the available input parameters. For the particular example, the inputs to the SSO will be:

- Inputs to the generic scheduler: i.e. all traditional scheduling parameters plus energy consumption data.
- Social KPIs: KPIs regarding personnel and the shop floor (more exemplary info in table 1).
- Emissions KPIs: KPIs regarding shop floor and associated pollutant emissions (more exemplary info in table 1).

Each KPI becomes part of the evaluation (or fitness) function and is assigned its own weight. The sum of these weights is used to evaluate the proposed solutions. The KPIs will be quantified with a common quantifier, i.e. €-value per unit of KPI, e.g. EU emissions trading scheme.

Objective Function = $w_1KPI_1 + w_2KPI_2 + w_3KPI_3 + \ldots + w_nKPI_n$, where $0.0 \leq w_i \leq 1.0$

The first main output of the SSO will be the optimized schedule for the generalized example based on the total sustainability in production. Alterations or even exclusion of KPIs can be made to demonstrate its operation under the varying conditions of a shop-floor or manufacturing facility over time.

Once scheduling for total sustainability has been achieved, the next step towards the Factory of the Future is to enable adaptability and flexibility of the traditionally rigid production process. As a secondary output, the SSO will address two functions that are typically viewed as separate: scheduling and process planning.

Through this view, the SSO will be able to propose alternative process layouts and accompanying schedules in such cases as machine breakdowns, rush orders, etc. Thus while retaining the actual physical machine layout, alternative process layouts can be proposed depending on the individual shop-floor and machine parameters at the time.

Table 1 – Social and emissions KPIs for the generalized example UC

	Performance Index	Comments
Economic	**Overall Equipment Effectiveness (OEE)**	Overall Equipment Effectiveness (OEE) is a function (product) of three PIs/KPIs: Availability (Equipment), Performance & Quality.
	Availability	Percentage of actual Production Time over the scheduled Production Time
	Performance Efficiency	Performance Efficiency is a measure of how a machine (or system) performs compared to the expected (designed) performance
	Scrap Ratio/Quality	Scrap Ratio indicates the percentage of scrap Units produced. Quality is equal to inverse.
Environmental	**Energy consumption**	Energy Consumption is the sum of all energy consumed including energy consumed by Machines, Lights, Cranes, Conveyors, etc.
	Energy Efficiency	For the specific UC, the Energy efficiency of a production schedule is the ratio of, a Default Energy amount required for the outputted PU, to the actual energy consumed. (Qualitative)
	Saved Energy	For the CRF-UC, Saved Energy is the difference between Default & Actual energy consumption (kWh
	CO2 Direct	CO2 direct emissions by an organization's facility or process. The figures are based on the overall sustainability reports & tables of the factory.
	CO2 Indirect	CO2 indirect emissions by an organization's facility or process (from the electrical energy provider). The figures are based on the overall sustainability reports & tables of the factory.
Social	**Injuries Rates (vs Work Patterns)**	Injury Rate (per 100 Workers) indicate the rate of incidents that cause Absenteeism & Lost Working Days. Details and statistics from Factory, HSE, ACOEM & OSHA reports [] are used to compile the required rates.
	Lost Time / Absenteeism	Absenteeism indicates the frequency of Lost Time Injuries (LTIs)

A large number of Measured Values (MVs) and intermediate Performance Indices (PIs) is involved in the calculation of the above mentioned Key Performance Indices (KPIs), such as: Production Time, Scheduled Production Time, Designed Cycle Time, Actual Operating Time, Produced Units, Irreparable Units, Energy Tariff, Energy Consumption, Total Man-hours, Productivity, Work-Pattern, etc. The relationships between MVs – PIs – KPIs are depicted in the following graph (figure 5).

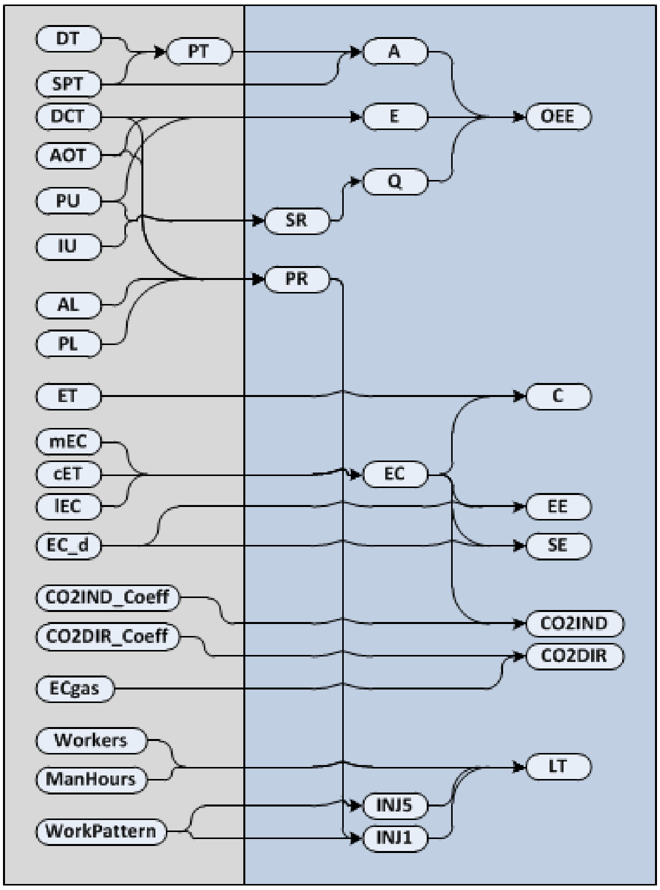


Figure 5 - The relationships between MVs – PIs – KPIs

SSO Role & Workflow

SSO operation is following the SMES flow of operations. After the system initialization and production scheduling, SSO can be invoked to provide alternatives (figure 6).

Given a SMES, SSO is called by the operator or the system, whenever appropriate to calculate and submit a further optimized schedule that will satisfy sustainability issues.

SSO connects to the MB and is waiting for a request about an optimized plan, i.e., it waits to receive a message asking for a Schedule/Optimization. This request to SSO could be submitted manually and also automatically especially when a significant change has occurred such as a bottleneck or a tool down or any other event that requires re-calculation of the plan

Implementation

SSO core is an optimization module that is developed and implemented in MATLAB. It is a standalone component that is installed in a machine equipped with an IIS web server, and it is offered as a web service to the FoFdation framework (figure 7). SSO core installation requires the presence of the MATLAB Runtime Compiler, but only in the web server that hosts the web service, therefore no installation instructions are required for the end-user. SSO interface is the I/O handling module that also includes the Web Service part and is implemented in ASP.NET C#.

SSO Web Service is registered to the SMES Message Broker and enables the message exchange between SSO core and SMES or any other component. An auxiliary “push” Web Service is also enabled in order to receive messages form the Message Broker

SSO input data will include all relevant inputs regarding scheduling and sustainability. The required inputs will be retrieved via the Message Broker (figure 7). Alternatively SSO will be able to accept the input data via a GUI front end to facilitate manual tests.

The data will be requested from the MIP, the OLAP service, the Scheduler, the Sustainability Evaluator, the

ERP, or a corresponding MES subsystem.

The major input sets are:

- The set of inputs provided for the MES scheduler (i.e., machine characteristics, production line, etc).
- The set of Social KPIs.
- The set of Emissions KPIs.

The SSO output is a modified schedule that follows the MES Scheduler output format, i.e. a Gantt chart and a table of the modified schedule.

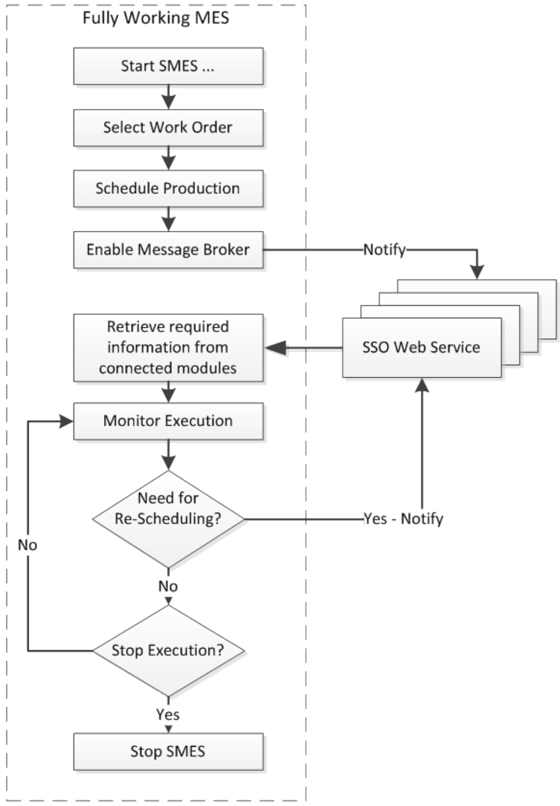
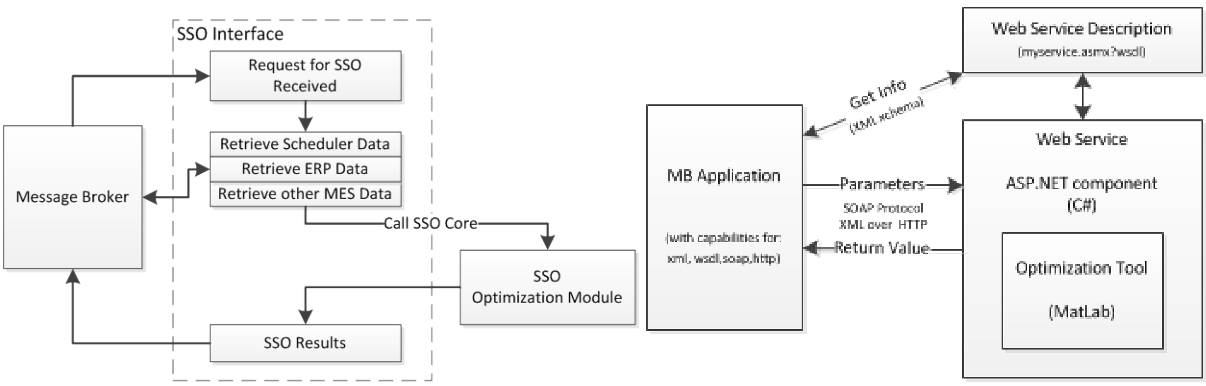


Figure 6. Simplified SMES workflow that implements the SSO concept.



(a) (b)

Figure 7: a) SSO interfacing with MES through MB, and b) the SSO web service and core modules.

A heuristic example of what might be an SSO optimized alternative process layout in the case of a single machine breakdown is shown in figure 6. If M21 from OP50 goes out of order in the middle of production, M17 from OP40 is re-tooled, re-programmed and re-assigned to OP50 and M13 from OP30 is shut down.

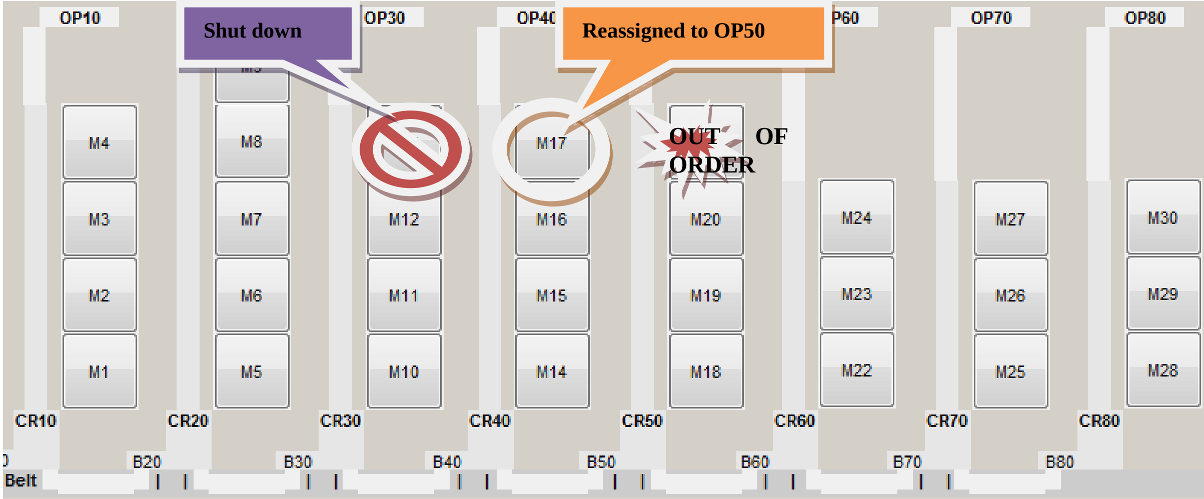


Figure 8 – Heuristic example of alternative process layout by SSO in case of a single machine breakdown

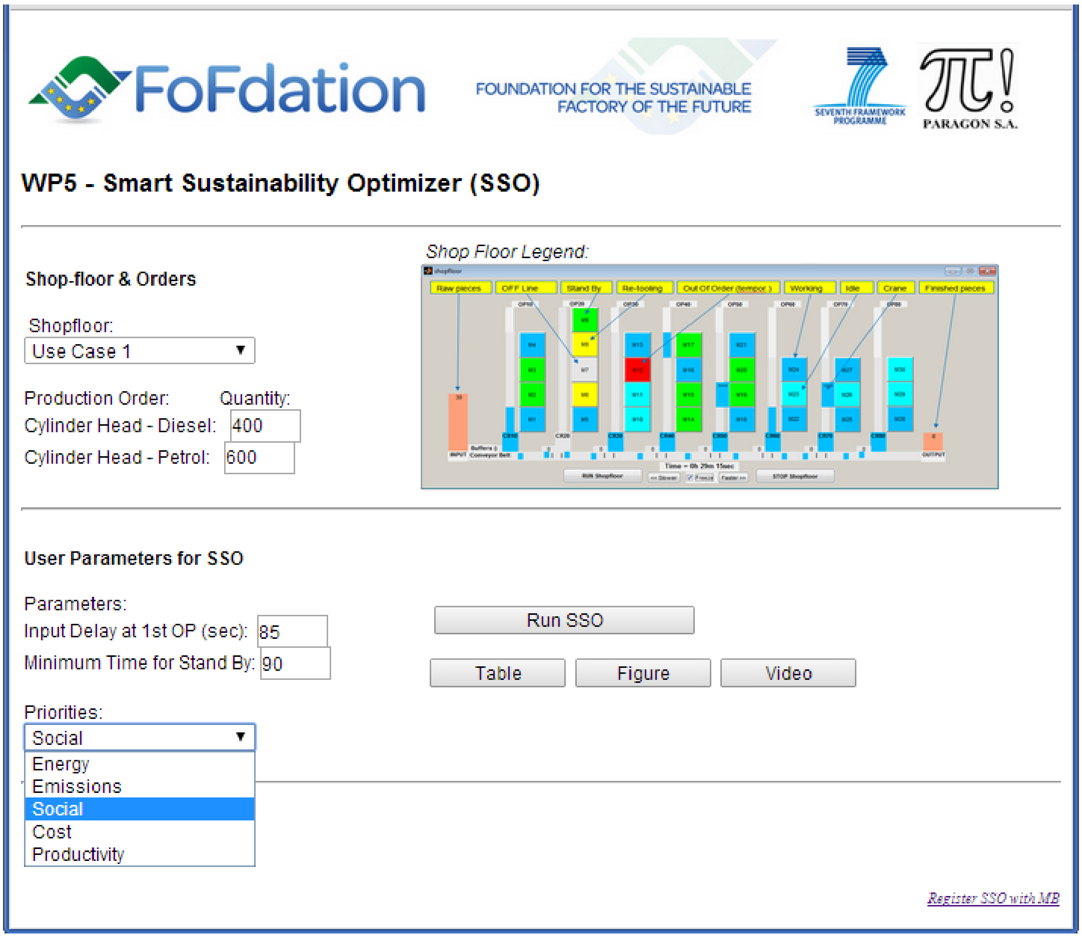


Figure 8: SSO web user interface

5 CONCLUSIONS

In this document, the concept of the Smart Sustainability Optimization performed by Paragon in the FoFdation project was presented, to better illustrate what Smart Sustainability Optimization is and how it forms an integral part of the SMES functionality for sustainability scheduling beyond any MES Scheduler and for investigation of potential shop-floor dynamics/flexibility. The SSO is an advanced tool aiming to optimize production schedule for total (TBL) sustainability (energy, social, emissions) and to propose alternative process layouts and accompanying schedules in cases of unforeseen problems (e.g. machines breakdowns, rush orders, etc.) without disturbing the physical layout of the shop floor.

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