Life-cycle Approach to Extend Equipment Re-use in Flexible Manufacturing

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Life-cycle Approach to Extend Equipment Re-use in Flexible Manufacturing

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Abstract—Nowadays, manufacturing industry has to adapt quickly, with minimum effort, to constant changes on customer demand. On the other hand, concerns regarding the environmental and social impacts of industrial processes is growing. These are ideas behind the project Innovative Reuse of modular knowledge Based devices and technologies for Old, Renewed and New factories (ReBORN). This paper presents the System Assessment Tool, a software application developed in ReBORN, which is used for assessing the sustainability of highly adaptive production systems. The main objective of this evaluation tool is to provide methods and algorithms for assessing the various (re)configuration possibilities and the corresponding effect on the overall system cost, performance and status throughout the entire life-cycle(s) of the manufacturing system. In order to help the system designer to make more informed decisions, different factors relating the life-long assessment of the concerned system and device were taken into account. This results in the optimum utilization of the manufacturing equipment throughout their life-cycle.

Keywords–Smart factories; Life-cycle assessment; Re-use; Production systems.

I. Introduction

The ReBORN project - Innovative Reuse of modular knowledge Based devices and technologies for Old, Renewed and New factories - is a project co-funded by the European Commission, which intends to demonstrate strategies and technologies that enable the re-use of production equipment in old, renewed and new factories. The idea is to save valuable resources by re-cycling equipment and use it in a different application, instead of discarding it after one way use. Currently, there is a lack of versatile and modular, task-driven plug&produce devices with built-in capabilities for self-assessment and optimal re-use. This requires new concepts and strategies for repair and upgrade of equipment, the (re-) design of factory layouts and flexible, adaptable and ready to plug-in modules. Such new strategies will contribute to sustainable, resource-friendly and greener manufacturing and, at the same time, deliver economic and competitive advantages for the manufacturing sector.

During its life-cycle, manufacturing equipment passes throw several stages, starting at initial incorporation into the production line, operation, maintenance/upgrade to end-of-use and disassemble. Throughout these stages there are a number of critical intersections, which can potentially cause costly machine downtime or even downtime in the entire production system. Usually, decisions regarding equipment operation are made by engineers and shop-floor operators, which are most of the times based on the experience of these individuals. Sometimes the individuals know-how and gained knowledge by experience is hard to be transferred to other individuals and may be lost [1]. In order to tackle this problem, a support to decision making must exist, combining simulations with the process data history gathered on equipment level. A System Assessment Tool (SAT) was implemented, allowing the analysis and comparison of industrial equipment, based on reliability metrics, Life Cycle Cost (LCC) and Life Cycle Assessment (LCA).

This paper is organized in four more sections. In section II, a brief overview of the ReBORN project is presented, along with a discussion regarding the current state of the art of the metrics used for equipment analysis. In section III, the System Assessment Tool is analyzed and described, followed by a demonstration scenario in Section IV. Section V concludes the paper by exposing some final remarks about the implemented software and next steps for future work are identified.

II. Life-cycle Cost Assessment

The vision of ReBORN is to demonstrate strategies and technologies that support a new paradigm for the re-use of production equipment in factories. This re-use will give new life to decommissioned production systems and equipment, helping them to be reborn in new production lines. Such new strategies will contribute to a more sustainable and resource-friendly and, at the same time, deliver economic and competitive advantages for the manufacturing sector.

ReBORN efforts are towards 100% re-use of equipment, focusing its approaches on four main areas: 1) modular Plug and Produce equipment, 2) in-line adaptive manufacturing, 3) innovative factory layout design techniques and adaptive (re)configuration, 4) flexible and low-cost mechanical systems for fast and easy assembly and disassemble. All the developments of the four areas together accumulate manufacturing knowledge for a 360 factory equipment life-cycle. These developments will give rise to self-aware and knowledge based equipment, with functionalities to collect and manage information regarding their capabilities. Through its approach and planned activities, ReBORN addresses industrial needs hitherto neglected and contributes to unleash the full potential of sustainable, green and smart factories, by empowering the industry to produce components and assembly systems, which can address fast changing requirements.

In ReBORN, several efforts are being done on the life-cycle cost assessment for adaptive system reconfiguration and change. The system reconfiguration and change is performed through the assessment of various reconfiguration possibilities, such as change, upgrade, reuse, dismantle and disposal, and the corresponding effect on the overall system cost, performance

and status throughout the life-cycle. This is accomplished by what-if simulation scenarios on the virtual agents representation of the equipment in the virtual design environment, in order to estimate the likely impact on the physical system before making a change recommendation.

Over the years several models, tools, and standards have been developed for reliability [2] [3], LCC [4]–[8], and LCA [9]–[12]. These three areas are usually treated as separate fields, where each one of them have their own metrics, tools, and standards. Some attempts to bring them closer have been made [13]–[15], where the relation between different sustainability assessment tools is presented, and the central concept is life cycle assessment for sustainability [16]. Several surveys of existing the methodologies and tools on all the three fields have been performed [7], [15]–[18].

Cerria, Taisch and Terzi on [19], proposed an integrated, structured and robust model to support and help the activity of designers and engineers to create and identify the optimal life cycle oriented solution. This solution takes into account some of the LCC, LCA, and technical constraints and/or performances methodologies. This work presented some results of the tests that were performed with an industrial case that look promising. Unfortunately the metrics used were not described and no further details were provided.

Although some steps have being made in order to correlate reliability, LCC, and LCA, there is still work to be done. This is what motivated us to develop our System Assessment tool.

III.   SYSTEM ASSESSMENT TOOL

The SAT integrates reliability and life cycle status information during the early design phases. This tool is a web based application that allows users to use it directly or through a REST web service.

The life-long cost assessment of the system is accomplished through the collection of the system performances data throughout its life cycle. Based on this performance data, the SAT performs the life cycle cost assessment and analyses the effect on the overall reconfigured system, by comparing machines and production lines. According to the requirements of the ReBORN consortium, this comparison is done based on three different metrics: 1) reliability (Fig. 4), such as failure rate, Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR), reliability, availability, performance, quality, and Overall Equipment Effectiveness (OEE); 2) LCC (Fig. 6), such as Future Value (FV), Present Value (PV), Net Present Cost (NPC), and Net Present Value (NPV) with initial costs; 3) LCA (Fig. 7), such as life cycle emissions.

A. Architecture

The SAT is a tool that has two main objectives: 1) provide an easy and intuitive way for the user to compare machines or production lines through a web application; 2) provide a web API service, able to receive requests and communicate the results with other modules in the project, or other future applications.

Both the web application and the web API service provide the same functionalities, which are depicted, at a high level, in Fig. 1.

The tool has four main groups, namely the Reliability metrics, LCC metrics, LCA metrics, and Machine Label. These functionalities are further described in the next sections.
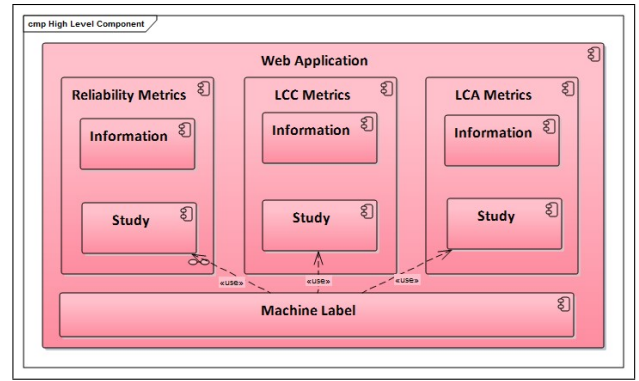

Figure 1. System Assessment Tool Overall Architecture

B. Reliability Metrics Functionality

The SAT can calculate the following parameters related to the reliability of operation of the machines or production lines:

- Failure rate, which can be defined as the frequency which an engineered system or component fails, expressed in failures per unit of time.

$$Failure rate = \frac{\#failures\ per\ unit\ of\ time}{Operating\ Hours\ per\ unit\ of\ time} \quad (1)$$

- MTBF is defined as the predicted elapsed time between inherent failures of a system during operation.

$$MTBF = \frac{Operating\ Hours\ per\ unit\ of\ time}{\#failures\ per\ unit\ of\ time} \quad (2)$$

- MTTR is a basic measure of the maintainability of repairable items. It represents the average time required to repair a failed component or device.

$$MTTR = \frac{\sum(breakdown\ times\ per\ unit\ of\ time)}{\#failures\ per\ unit\ of\ time} \quad (3)$$

- Reliability is the probability that the equipment will complete a mission of length t without failure. It is an exponential function.

$$Reliability = e^{-failureRate*time} \quad (4)$$

- Availability is defined as the ratio between the actual run time and the scheduled run time.

$$Availability = \frac{Operating\ Hours\ Year}{Planned\ Production\ Time} \quad (5)$$

- Performance is the ratio between the actual number of units produced and the number of unit that theoretically can be produced. It is based on the standard rate, which is the rate the equipment is designed for.

$$Performance = \frac{(Total\ Pieces * Ideal\ Cycle\ Time)}{Operating\ Hours\ Year} \quad (6)$$

- Quality is the ratio between good units produced and the total units that were produced.

$$Quality = \frac{Good\ Pieces}{Total\ Pieces} \quad (7)$$

- OEE is the ratio between the theoretical maximum good output during the loading time vs. the actual good output.

$$OEE = \text{Availability * Performance * Quality} \quad (8)$$

C. LCC Metrics Functionality

In the area of LCC metrics, the following parameters are calculated by the SAT:

- Capital Cost Unit Over Service Life, which is the cost of producing a unit over the machine expected service life.

$$\begin{aligned} CC = &\text{(Hardware Acquisition + Software Acquisition} \\ &\text{+ Service Contracts + Administrative} \\ &\text{+ Set Up Installation + Other Inicial Costs)} \\ &\text{+ ((Training Maintenance Support} \\ &\text{+ Materials Costs + Equipment Upgrade} \\ &\text{+ Other Operations Maintenance)} \\ &\text{+ ((Default Annual Energy Consumption} \\ &\text{* Eletricity Rate) * Machine Expected Service Life))} \\ &\text{+ Disposition Cost} \quad (9) \end{aligned}$$

- Capital Annualized Cost Unit is the cost of producing a unit per year.

$$CA = \frac{\text{Capital Cost Unit Over Service Life}}{\text{Machine Expected Service Life}} \quad (10)$$

- FV, which is the value of an asset or cash at a specified date in the future that is equivalent in value to a specified sum today. The idea is that an amount today is worth a different amount at a future time (this is based on the time value of money).

$$\begin{aligned} FV = &\text{(Hardware Acquisition + Software Acquisition} \\ &\text{+ Service Contracts + Administrative} \\ &\text{+ Set Up Installation + Other Inicial Costs)} \\ &\text{* } (1 + (\frac{\text{Interest Rate}}{100})) \text{ * Years to be analysed)} \\ & \quad (11) \end{aligned}$$

- PV is the present day value of an amount that is received at a future date.

$$PV = \frac{\text{Future Value Over Period Review}}{(1 + \frac{DiscountRate}{100})^{\text{Years to be analysed}}} \quad (12)$$

- NPC is the sum of all costs, such as capital investment, non-fuel operation and maintenance costs, replacement costs, energy costs (fuel cost plus any associated costs), any other costs, such as legal fees, etc. If a number of options are being considered then the option with the lowest NPC will be the most favorable financial option.

$$\begin{aligned} NPC = &\text{PV OverPeriodReview} + (\frac{\text{Discount Rate}}{100}) \\ &\text{* (total Cash Flows)} \quad (13) \end{aligned}$$

- NPV is used to determine the present value of an investment by the discounted sum of all cash flows received from the project and discounting the initial costs.

$$\begin{aligned} NPV = &\sum (\text{cash Flow * } \frac{1}{1 + \frac{\text{Discount Rate}}{100}}^{\text{Period Review}} \\ &\text{- Initial Costs} \quad (14) \end{aligned}$$

D. LCA Metrics Functionality

Life cycle assessment is a cradle-to-grave approach for assessing industrial systems. Cradle-to-grave begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth [10] [11].

According to [9] LCA had its beginnings in the 1960s due to concerns over the limitations of raw materials and energy resources. One of the first publications of its kind was done by Harold Smith, who reported his calculation of cumulative energy requirements for the production of chemical intermediates and products at the World Energy Conference in 1963.

The realization of an LCA study is a complex process that needs a large amount of different data that usually is not commonly available. Due to that fact, simpler metrics related to the environmental impacts were considered. The following commonly study impacts were considered: Global Warming, Stratospheric Ozone Depletion, and Human Health. Each one of these impacts has a characterization factor associated to it:

- Global Warming factor has as characterization factor the Global Warming Potential. To calculate this impact, several types of flows must be taken into account, such as Carbon Dioxide (CO2), Nitrogen Dioxide (NO2), Methane (CH4), Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), and Methyl Bromide (CH3Br).

$$\begin{aligned} GWP = &\text{(CO2*1)+(CH4*25)+(CH3Br*5)} \\ &\text{+(N2O*298)+(SF6*22800)*(NF3*17200)} \quad (15) \end{aligned}$$

- Stratospheric Ozone Depletion has as characterization factor the Ozone Depleting Potential. To calculate this impact, several types of flows must be taking into account, such as: Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), and Halons Methyl Bromide (CH3Br).

$$\begin{aligned} ODP = &\text{(CCl3F(CFC11)*1)+(CCl2F (CFC12)*1)} \\ &\text{+(C2Cl3F3(CFC113)*1.07)+(C2F4Cl (CFC114)*0.8)} \\ &\text{+(C2ClF5(CFC115)*0.5)+(HClFC2 HCFC22)*0.055)} \\ &\text{+(CH3CCl3(HC140a)*0.12)+(CF3Br(Halon1301)*16)} \\ &\text{+(CF2BrCl(Halon1211)*4)} \\ &\text{+(CCl4(Tetrachloromethane)*1.08)} \quad (16) \end{aligned}$$

- Human Health has as characterization factor the LC50. To calculate this impact, several types of flows must be taking into account, such as Carbon Monoxide (CO), Oxides of Nitrogen (NOx), and Sulphur Dioxide (SO2).

$$HH = \text{(CO*0.012)+(NOx*0.78)+(SO2*1.2)} \quad (17)$$

E. Machine Label

The Machine Label main objective is to attribute a grade from A to F to the machines, based on the metrics calculated and represented on Table I. The basic idea is to attribute weights to selected metrics and determine the grade based on these weights. The goal is to have an equipment label similar to the European Union energy label [20].

TABLE I. LABEL SCALE

Grade	Range (%)
A	100-90
B	89-70
C	69-50
D	49-30
E	29-10
F	10-0

As a first approach, this grade is defined using (1), represented by a few metrics and identical weights. Label is the grade, R and Rw are the reliability and reliability weight, OEE and OEEw are the overall equipment effectiveness and respective weight, Oc, Ic and DOc are the operational cost, the initial cost and dispose off cost, EC and ECw are the energy consumption and respective weight, PR and PRw are the percentage reusable and the corresponding weight. Sensitivities studies to determine a more robust metric to determine the attribution of the machine label are ongoing.

$$Label = R*Rw + OEE*OEEw + ((Oc)/((Ic+DOc)*Weight) + EC*ECw + PR*PRw$$

$$(18)$$

IV. DEMONSTRATION SCENARIO

As mentioned before, the ReBORN aims to develop a general design methodology for manufacturing systems, building on the availability of great amounts of data and knowledge of life and use of production equipment collected by the devices, with the purpose of enabling new system design methods with extensive re-use of production equipment.

The design methodology is based on the concept of component-based agent representation of modular manufacturing equipment [21] [22], where every piece of equipment is controlled through an intelligent agent that continuously captures knowledge about the current status of the equipment. This information about the task-related efforts, the prospective lifetime, maintenance- and refurbishment-related needs as well as enhancement-related needs allows for the formulation of an overall cost function and for the optimum choice of new, re-use, refurbished or enhanced production equipment.

In order to implement the defined methodology, several software applications where developed by the ReBORN consortium, which are integrated in a workbench developed by Critical Manufacturing company [23], as shown in Fig. 2. This workbench application manages links to the set of tools that will allow a user to build the best possible layout and configuration for a factory, given a set of requirements, constraints and goals.

The SAT can be used inside of the ReBORN workbench or it can be used as an independent software application.

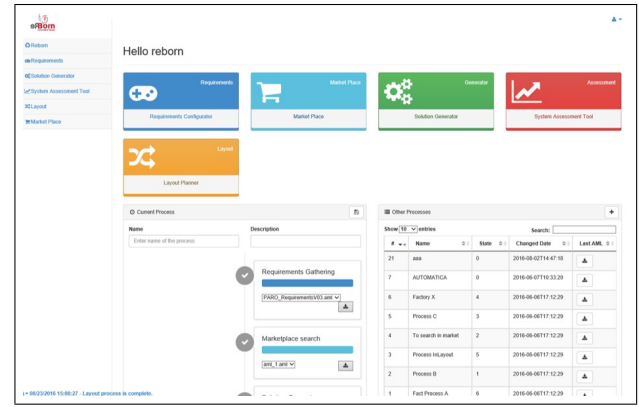The SAT web application main page is shown in Fig. 3.
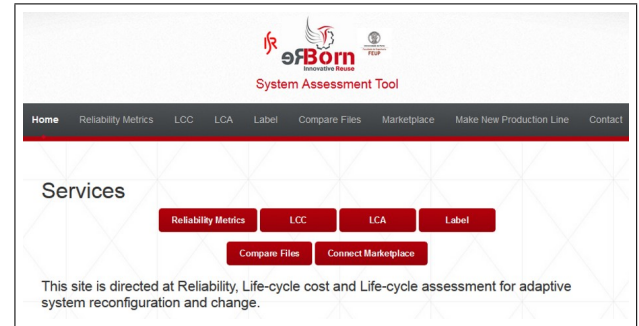

Figure 2. ReBORN Workbench

Figure 3. System Assessment tool main web page

As shown on Fig. 3, SATs main tab presents the core functionalities described in the previous sections, namely Reliability, LCC, LCA, Label, and Compare files.

Each of the functionalities has two main sub-functionalities: 1) Information, which deals with all the operations related to adding a new machine or production line, changing them or deleting them; 2) Study, which performs the comparison between several machines or production lines.

The following images show all the possible functionalities and how the results of the studies are shown. As mentioned before, the information can be introduced through the web pages or through an XML file. This applies to both Information and Study. After a Study is executed, the results can also be stored in a XML file.

Fig. 4 presents the graphics view that represents the result of comparing equipments or production lines.

In the LCC study, besides choosing the machines or production lines to be compared, other information must be selected or provided, such as review periods in years, country to be considered, machines or production lines to be compared, and finally the cash flows values for the years, up to the maximum review period, for the machines or production lines under comparison. The LCC study steps are represented in Fig. 5.

Fig. 6 presents the charts generated after the selected equipment or production lines are compared.

Fig. 7 shows the result charts of the comparison of equip-

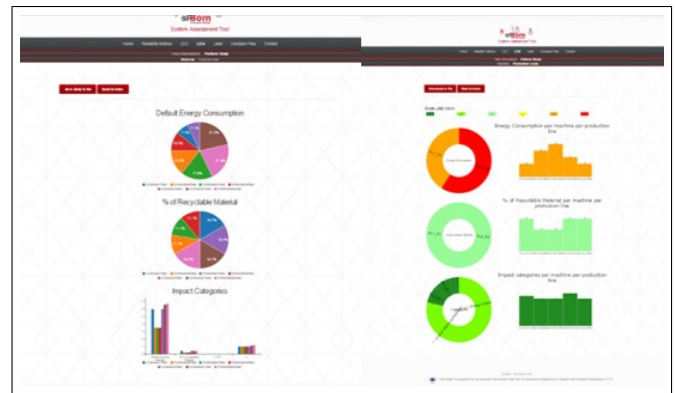Figure 4. Reliability Study Views
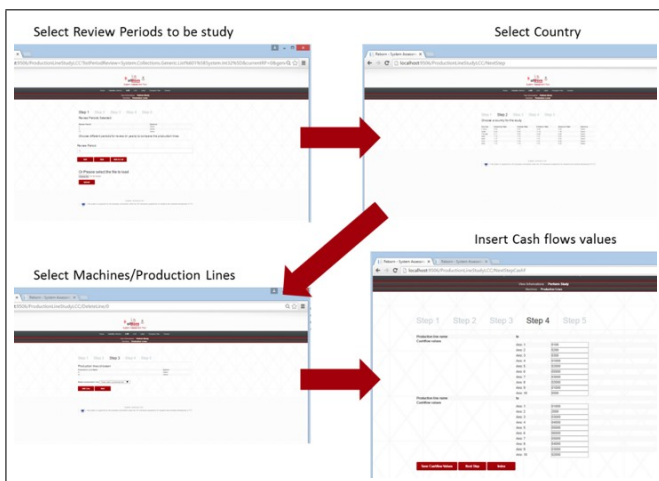

Figure 7. LCA Study Views

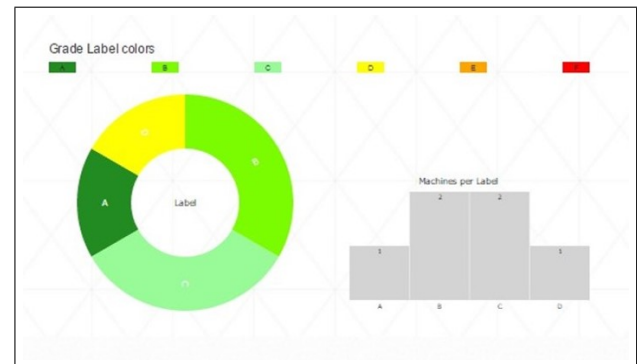

Figure 5. LCC Study steps
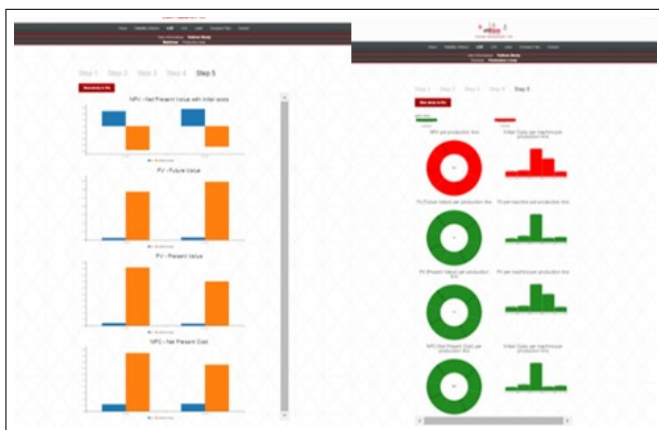

Figure 8. Label View

Figure 6. LCC Study results Views

ment and production lines in terms of LCA metrics.

Fig. 8 presents the charts showing the result of calculating the equipment label.

As mentioned before, the System Assessment tool can be used through the upload of XML files or through the Web API service, allowing flexibility and easy collaboration with other software tools, such as simulators. For example, a simulation tool, such as the FlexSim [24], can be used to simulate the production line, and collect different data. This data can be exported and feed into the SAT.

As a practical example let us assume that a company, in our case one of the industrial partners in the ReBorn project, such as Fagor Automation, PARO, or Harms & Wende, needs to change or acquire an equipment. Using the SAT, new and used equipments can be easily compared. For example, if the idea is to compare them in terms of financial advantage, the SAT allows to compare, for several periods of time, the equipments (or production lines). The result is presented in a straightforward way through the use of circular or bar charts, as shown in Fig. 5. A visual comparison of the charts, allows the industrial partners to realize that if the equipment that they need is going to be used for a short period of time, it makes sense to buy a used equipment. On the other hand if the equipment is going to be used for a long period of time it is reasonable to buy the new equipment.

This type of comparison can be performed considering other aspects besides the financial ones, such as operational factors (reliability, MTTB, MTTR, OEE) or environmental factors (Global Warming, Stratospheric Ozone Depletion, Human Health). The results are also presented visually as in the financial related case (Fig. 7).

As mentioned before, there are several tools that calculate the metrics used in the SAT, but most of the tools concentrate on a specific area, operational, financial, or environmental. One

of the advantages of the SAT is the ability to have all these metrics in just one tool. The SAT also proposes a way of easily comparing equipments through the use of a Label, much like the energy label used to classify other equipments, such as refrigerators, TVs, etc.

Always keeping in mind the easy usability of the application, all the information needed to perform the metrics can be introduced through the web interface or through a file. Two types of files are so far supported: XML or AutomationML (AML). The SAT also has a compare files functionality. This functionality purpose is to enable the user to compare several machines or several production lines. This comparison will be able to perform all the metrics of the SAT, namely reliability, LCC, LCA, and Label. The information of the several machines or the several production lines to be compared will be supplied in XML or AML files.

V. CONCLUSION

A System Assessment tool was developed. This is a software web application that allows the comparison of several machines or several production lines in terms of different metrics, such as reliability, LCC and LCA. A System Assessment Web API was also developed. This is a web service based on REST, which can receive requests to calculate the metrics specified in the previous sections.

The purpose of this System Assessment tool is to support the decision making during the planning and running phase of complex manufacturing systems.

As future work a sensitivity analysis on the metrics used and of the parameters available, will be executed. This analysis will provide a clear view of what metrics and parameters really influence and are important when comparing machines.

ACKNOWLEDGMENT

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