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Proposal of a Closed Loop Framework for the Improvement of Industrial Systems’ Life Cycle Performances: Experiences from the LinkedDesign Project

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Abstract

The context where European manufacturers of industrial systems operate has dramatically changed over recent years: the pressure of emerging countries they have to face, policy makers’ environmental laws and industrial companies’ interests are pushing towards sustainable manufacturing and a holistic view of industrial systems. Designers and system engineers are the main actors involved, because they have high influence on product life cycle costs and environmental impacts. However they need tools to pursue a holistic view. The aim of this paper is to propose a closed loop framework to improve life cycle performances of industrial systems, focusing on the automotive sector.

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Keywords: Life Cycle Costing; Life Cycle Assessment; Life Cycle Performances; Closed Loop; Product Lifecycle Management.

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1. Introduction

LinkedDesign (http://www.linkeddesign.eu/) is a project, funded by European Commission, regarding the development of an IT platform, called LEAP (Linked Engineering mAnufacturing Platform), to federate all product lifecycle information and to provide specific knowledge exploitation solutions, like decision support systems to analyze the integrated information. The aims of this platform are four: (i) Data federation, federating all relevant information, across trusted sources in the product lifecycle, independent of its format, location and origination time; (ii) Context-driven access and analysis of federated information, providing specific means like sentiment analysis and simulations to analyze the integrated information; (iii) User collaboration, using and extending lean principles and implementing a collaboration workbench enabling internal and external collaboration; (iv) Feedback into existing systems, providing tight connections to the federates systems, in order to push back enriched information to them. The project is driven by the challenges that European manufacturers of capital equipment have faced during the last years: economic crisis, globalization and pressure of emerging countries, policy makers’ environmental laws and industrial companies’ interest. Therefore, structural changes in manufacturing industry are occurring, and new trends and paradigms such as sustainable manufacturing and mass customization. In this paper, the aim is to answer the sustainability need of European manufacturers of capital equipment through a holistic approach of the systems, proposing a closed loop framework to improve life cycle performances, in terms of cost and environmental impact, and to support designers, the main stakeholders, in their activities.

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Indeed, different empirical researches have been conducted to evaluate the percentage of life cycle cost or life cycle environmental impact influenced during the design phase. Blanchard [1], Dowlatashi [2], Munro [3], Sanders and Klein [4] state that product design represents 5-10% of life cycle cost; however, product design influences up to 80% of life cycle cost. The same consideration, about life cycle environmental impact, is reported by Rebitzer et al. [5]. To evaluate costs and environmental impacts generated during the whole life cycle, Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) are used. Life Cycle Costing is described as the methodology that enables to evaluate the total cost of ownership of a capital equipment, including its cost of acquisition, operation, maintenance, conversion and/or decommission [6]. Life Cycle Assessment, instead, is a methodology to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave [7], described in the standard ISO 14040 [8].

As previously cited, the objective is to propose a closed loop framework to improve life cycle performances of capital equipment. Furthermore, it wants to cover an existing lack: current PLM (Product Lifecycle Management) applications employ many systems and methodologies collecting product information, especially covering design, but not the product use phase; in particular feedbacks and data collected from the field are missing, although the tons of information collectable thanks to the continuous innovation and utilization of ICT systems. At the moment, the framework doesn't consider the product end of life, which will be implemented in a second step.

Paper is organized as follow: Section 2 introduces the lifecycle of a generic industrial system for automotive sector. Section 3 shows the closed loop framework, explaining how to apply it and giving a brief overview of different tools. Section 3.1, 3.2, 3.3, 3.4 and 3.5 flesh out the different tools, explaining in detail their academic background and their working. Finally, Section 4 concludes the paper, showing the next steps.

2. Lifecycle of an industrial system for automotive sector

In LinkedDesign project one of the industrial case is represented by an Italian global supplier of industrial automation systems and services mainly for the automotive manufacturing sector. The company offers its proficiency as system integrator and its complete engineering solutions, from product development and manufacturing, to assistance the production start-up phases, equipment and full plant maintenance activities. Fig. 1 shows the lifecycle of a generic systems (production line, assembly line, etc.). Concept phase is research and limited development or design, and it usually ends with a proposal. During this phase, customer (car manufacturer company) and supplier must work together in order to establish system requirements. Customer evaluates proposals of different suppliers: the best one in term of life cycle costs (and life cycle environmental impacts) gets the order. This is the most critical lifecycle phase. If the order is won, the lifecycle continue with the development design phase, the detailed design of the industrial system. Build and Install is the phase where the industrial system is manufactured and assembled in the customer plant and this phase concludes with the ramp up of the system. During Operation and Support phase the system is fully operating. In this phase collection of data from the field could be really interesting, in order to increase the knowledge of their systems on behalf of supplier and, therefore, to improve the life cycle performances (in terms of costs and environmental impacts) for the next proposals and to keep under control the behavior of existing systems.

Fig. 1. System Lifecycle of an industrial system for automotive sector

Finally, during Conversion and/or Decommission, system's conditions are evaluated, in order to decide which is the best option (reuse as is, conversion to a new state, dismissal, etc.)

3. Product Lifecycle Closed Loop Framework

In this section the Product Lifecycle Closed Loop Framework is proposed, and a general overview is given. Different components are briefly presented in this section, and then they will be fleshed out in the next sections. Fig. 2 describes the framework proposed. Into the Fig. 2, the components reported in red (LCC/LCA Service, Chart based Reporting Service, QLM (Quantum Lifecycle Management), PLM (Product Lifecycle Management) Data Service, Ontology Rules) have been developed within LinkedDesign project. Some components are called "Service", because they are services provided by LEAP.

During the concept phase, LCC/LCA Service is applied. It is composed by two parts: the first one to transform data in costs and environmental impacts, the second one, the so called PLCO (Product Life Cycle Optimization) to find the optimal life cycle oriented solution, building a model with two objectives (to minimize lifecycle costs and environmental impacts) that have to respect a series of constraints (based on customer requirements). LCC/LCA Service supports the designers/system engineers' activities for the creation and identification of the optimal solution and for the definition of a proposal for the costumer. Designers define the system boundaries and the costs and environmental impacts therein included and that they want to consider in the analysis. Furthermore, Chart based Reporting Service enable the information sharing within the company and not only within the designers' team.

If the proposal is the best submitted, the order is won. Therefore, in the following phases, system is design in detail and then built, assembled and installed in the customer plant. After the ramp up phase, where system is conducted to the full operating functioning, system enters in the use phase. During this phase, it is possible to collect data from the field, directly from the different sensors installed on the system, using QLM standards (published by The Open Group). Data collected are analyzed by PLM Data Service, providing feedbacks to the designers and system engineers, in order to: (i) update the existing database with data from the field; (ii) improve LCC/LCA Service estimation accuracy; (iii) compare LCC/LCA Service estimation with real data and (iv) understand the behavior of the system, in terms of technical performances, during the use phase. Within this framework,

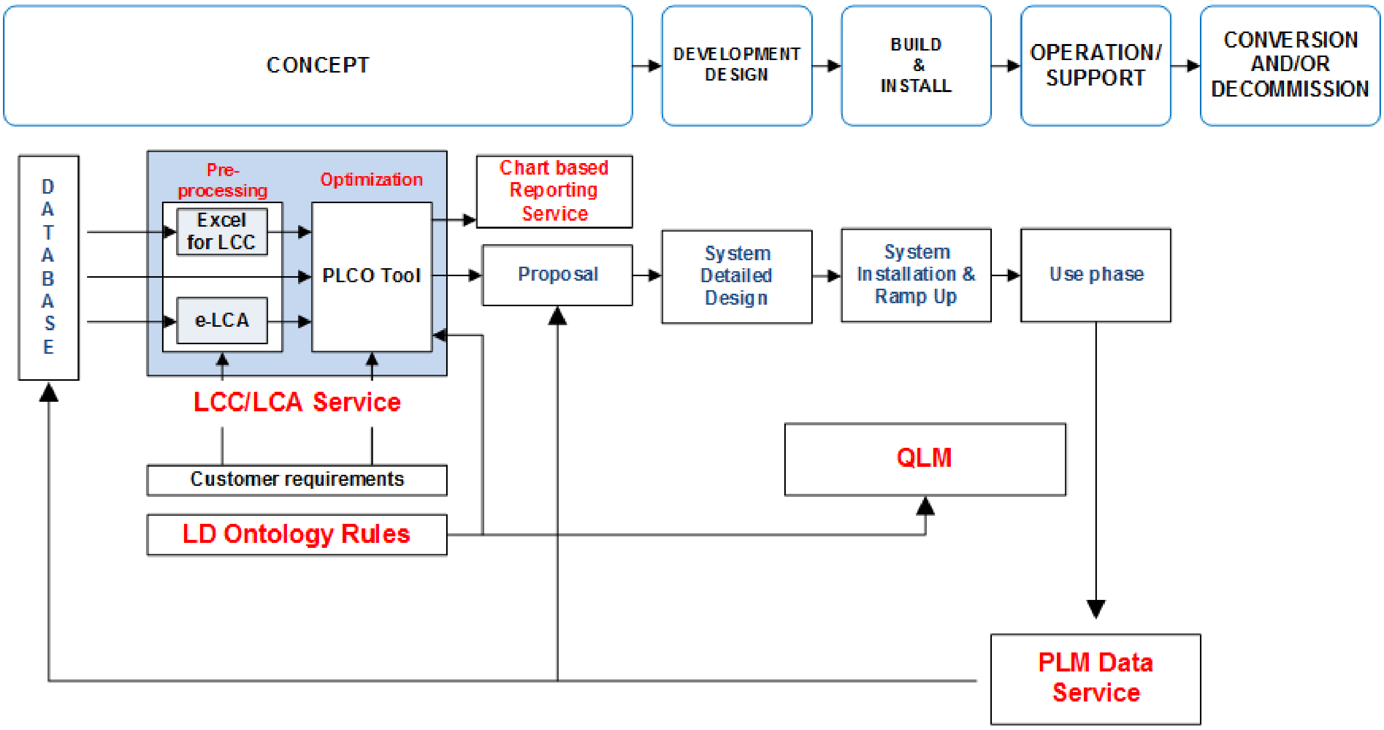


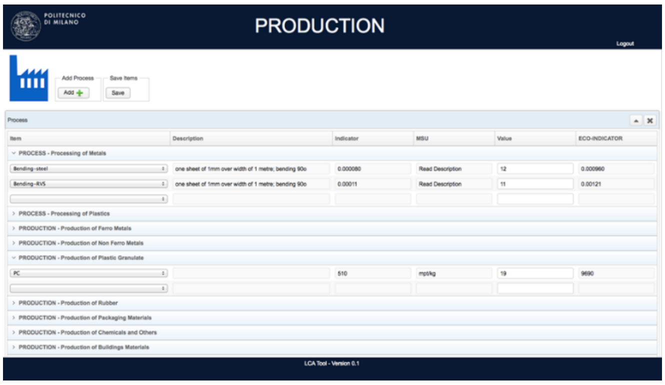
Fig. 2. Product Lifecycle Closed Loop Framework

Ontology Rules enables the generation of alarms for both LCC/LCA Service and QLM, in order to indicate if the system doesn't respect constraints/ customer requirements / thresholds.

3.1. LCC/LCA Service

LCC/LCA Service is built by two components: the first one, called Pre-processing, is necessary to prepare the input for the second component, called Optimization. Data are elaborated with data coming from customer, in order to prepare life cycle costs and life cycle environmental impacts. Excel Spreadsheets are used to calculate each single voice of cost. For environmental impact, instead, it is necessary something of more structured and complex. Therefore, e-LCA tool is developed (Fig. 3). The tool is a Java Web Application, and provides a quick and intuitive way for designers and engineers to understand, analyze and compare environmental impacts of products and of particular design decisions. In order to perform a streamlined analysis the tool has been conceived for evaluating only the three main phases of the product lifecycle, called: (i) production (processing of raw materials, manufacturing, packaging and marketing processes, transports), (ii) use (use, and maintenance of the product) and (iii) end of life (eventual recycling or re-use or disposal as waste). The e-LCA uses Eco-Indicator 99 [9] data as its main data source. Eco-Indicator 99 is older than other life cycle impact assessment (LCIA), however, it is chosen because it is one of the most widely used impact assessments in LCA [10]. Furthermore, Eco-indicator computes easy to use standard indicator scores. These single scores can be used as a user friendly tool by designers and product managers [9]. To realize the tool interface, ZK [11] is used.

PLCO (Product Life Cycle Optimization) tool is the second component of LCC/LCA Service. It enables to optimize



Item	Description	Indicator	MSU	Value	ECO-INDICATOR
PROCESS - Processing of Metals					
Bending-steel	one sheet of 1mm over width of 1 metre; bending 90o	0.000080	Read Description	12	0.000960
Bending-RVS	one sheet of 1mm over width of 1 metre; bending 90o	0.00011	Read Description	11	0.00121
PROCESS - Processing of Plastics					
PRODUCTION - Production of Ferro Metals					
PRODUCTION - Production of Non Ferro Metals					
PRODUCTION - Production of Plastic Granulate					
PC		510	mpt/kg	19	9690
PRODUCTION - Production of Rubber					
PRODUCTION - Production of Packaging Materials					
PRODUCTION - Production of Chemicals and Others					
PRODUCTION - Production of Buildings Materials					

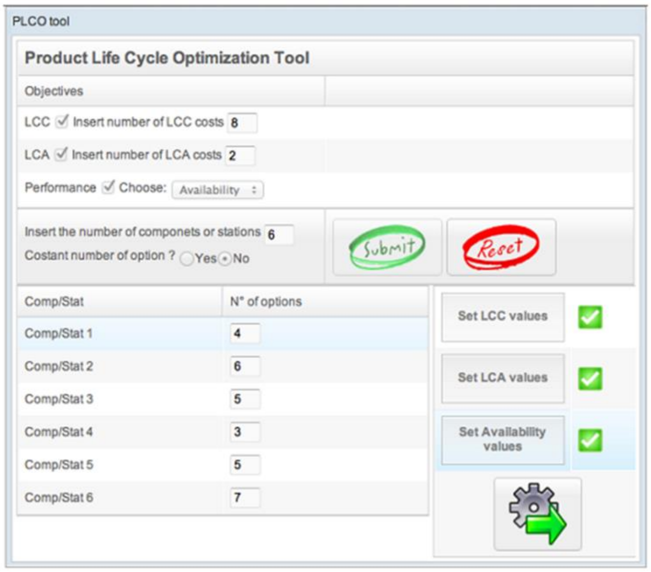
LCA Tool - Version 0.1

Fig. 3. Screenshot of e-LCA tool (Production)

together both costs and environmental impacts sustained along the whole product life cycle.

Before developing it, a deep study was conducted to define the academic background. Cerri et al. [12] analyzed literature to identify if and how the costs and environmental impacts of whole product lifecycle are in some way optimized. Then, genetic algorithm was defined as the most promising method for the following reason: (i) it is more efficient than other when the numbers of variables increases; (ii) it presents no problem with multi-objective optimization and (iii) it is suitable for applications dealing with component-based system (a product could be seen as a chromosome and its components as genes). In particular, NSGA-2 [13] is chosen, because it is one of the most popular and tested genetic algorithm. A model for Life Cycle Optimization, based on NSGA-2, was compared to two other optimization methods, based on linear programming, in order to check the soundness of the proposed model. To compare the three optimization methods, it was presented an experimental scenario composed of a preliminary set of three simplified test cases, where NSGA-2 resulted better than linear programming-based models.

PLCO tool [14] is then developed, using ZK [11] to create the front-end (Fig. 4), and JMetal [15] (a library to develop and study meta-heuristic to solve multi-objective problems) to create the back-end.



LCC ☑ Insert number of LCC costs 8
LCA ☑ Insert number of LCA costs 2
Performance ☑ Choose: Availability
Insert the number of componets or stations 6
Costant number of option ? ○ Yes ● No

Comp/Stat	N° of options
Comp/Stat 1	4
Comp/Stat 2	6
Comp/Stat 3	5
Comp/Stat 4	3
Comp/Stat 5	5
Comp/Stat 6	7

Fig. 4. PLCO front-end

3.2. Chart based Reporting Service

In order to support decision making in the analysis of life cycle performances, a novel collaborative approach is adopted. Typically life cycle performances involve several people in a company. Therefore, it makes sense to share results of an analysis between all teams in all phases of a product lifecycle (production, marketing, maintenance, testing, sales …) across multiple locations. One key concept of knowledge sharing especially connected to the area of Business Intelligence is the report. A report is a visualization of a query applied on certain data sets. Reports are traditionally used by business experts using tools such as spreadsheets for creating charts and tables demonstrating the knowledge insights. The goal of the collaborative chart-based reporting is to combine the insights gained from charts with a collaborative sharing and working with those fed by the input of knowledge exploitation.

Fig. 5. Chart-based Reporting Widget

A system, which distributes all the information between work groups, regardless of their location, is developed. Changes in viewing, adding, removing, resizing, etc. are synchronized among the participants. The core of the system builds upon an abstraction of a report that can be consumed by many different reporting tools such as excel, SAP BI Solutions or another vendor specific BI-Tool. Moreover, with the help of SAP Streamwork a collaborative widget for viewing and sharing of spread sheet based charts could be implemented. Fig. 5 shows a screenshot of the collaborative charting tool for knowledge visualization. It allows to search for charts and interact with them in a synchronized way. Any interaction of one user is synchronized with the others so that selections of measures and dimensions or zooming and panning is directly visible by other users in the group.

3.3. Quantum Lifecycle Management (QLM) standards of The Open Group

In the QLM world, communication between the participants, e.g. products and backend systems, is done by passing message between nodes using the Open Messaging Interface (O-MI). Where the Web uses the HTTP protocol for transmitting HTML-coded information mainly intended for human users, O-MI is used for transmitting Open Data Format (O-DF) represented IoT information mainly for processing by information systems. In the same way as HTTP can be used for transporting payloads also in other formats than HTML (such as O-MI messages in XML), O-MI can be used for transporting payloads also in other formats than O-DF. O-DF fulfills the same role in the IoT as HTML does for the Internet, meaning that QLM-DF is a generic content description model for things in the IoT (Internet of Things).

O-MI and O-DF specifications are written using XML schema due to its flexibility for describing complex data structures. Information encoded using O-DF can be used as payload also when using plain TCP/IP, HTTP or similar protocols. Indeed, O-MI and O-DF are independent entities that reside in the Application layer of the OSI model, as illustrated in Fig. 6, where O-MI is specified at the Communication level and O-DF is specified at the Format level. Therefore, both standards can be used independently of each other.

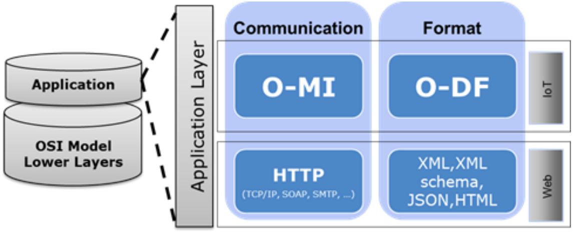
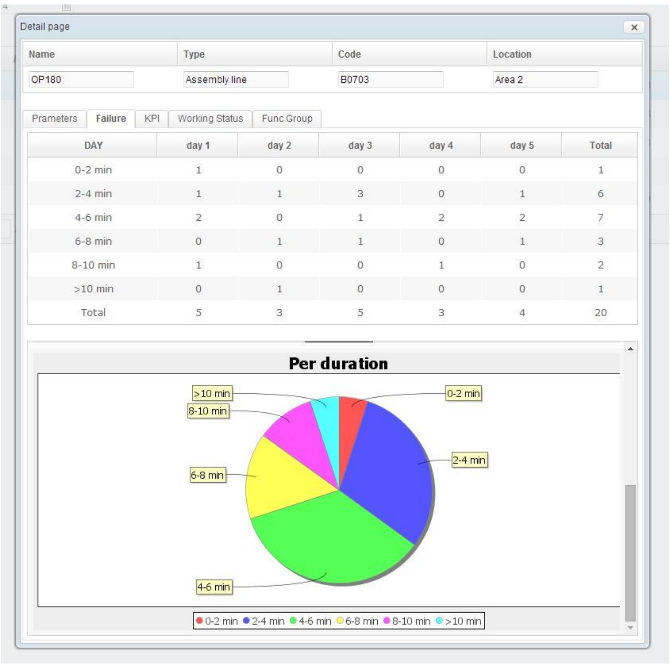


Fig. 6. Positioning of O-MI and O-DF in OSI model layers.

New standards are being developed by the QLM Work Group of The Open Group, which will provide domain-specific extensions for supply chain management, product lifecycle management, health-care and other relevant domains where such standards are missing.

3.4. PLM Data Service

PLM Data Service (Fig. 7) is used to retrieve and to present production and reliability data from the machine in shop-floor. It receives data in QLM format using REST web services or csv files. It presents manufacturing product related information (number of good pieces, number of scraps, etc.) and sensor parameters as failure duration, failure per station, failure per sub-group (of a station), cycle time, etc., collected during the manufacturing process. The tool elaborates collected information showing in a graphic way the machine status, warnings and failures with related duration, useful to implement a real time monitoring of the machines during the operational phase. Finally information stored from the field are used to update LCC, LCA and R&M (Reliability & Maintenance) DBs in order to perform analysis with update data. Furthermore, it enables comparison between real data and estimated data (by LCC/LCA Service) and it is useful to understand the behavior (failure rate, availability, reliability, energy consumption, etc.) of the manufacturing system during the use phase.



Name	Type	Code	Location
OP180	Assembly line	B0703	Area 2

DAY	day 1	day 2	day 3	day 4	day 5	Total
0-2 min	1	0	0	0	0	1
2-4 min	1	1	3	0	1	6
4-6 min	2	0	1	2	2	7
6-8 min	0	1	1	0	1	3
8-10 min	1	0	0	1	0	2
>10 min	0	1	0	0	0	1
Total	5	3	5	3	4	20

Fig. 7. PLM Data Service: failure duration

3.5. Ontology Rules

LinkedDesign ontology (LDO) is designed based on a two layers approach: (i) an upper ontology describing generic concepts describing the domain of design and manufacturing and (ii) specialized ontologies, describing specific requirements of the domain such as quality control or life cycle cost [16]. The specialized ontologies are mapped and aligned with the upper ontology through modularization principles [17]. The main advantage of this approach is that practically any system dealing with design and manufacturing will be able to reuse the upper ontology with a little or no adjustments. This reduces the resources needed for design of ontology from the beginning. The design of LDO is based on the QLM model as an acknowledged structured knowledge addressing the requirements of the Closed-Loop Product Lifecycle Management [18], [19]. In order to cover the requirements of Closed Loop Framework, a specialized LCC ontology models the structure of all relevant and available costs describing the product design, manufacturing, maintenance and decommission [20], [21]. An extract of the graph representation of LCC ontology is given in Fig. 8, concepts properties are omitted here for clarity.

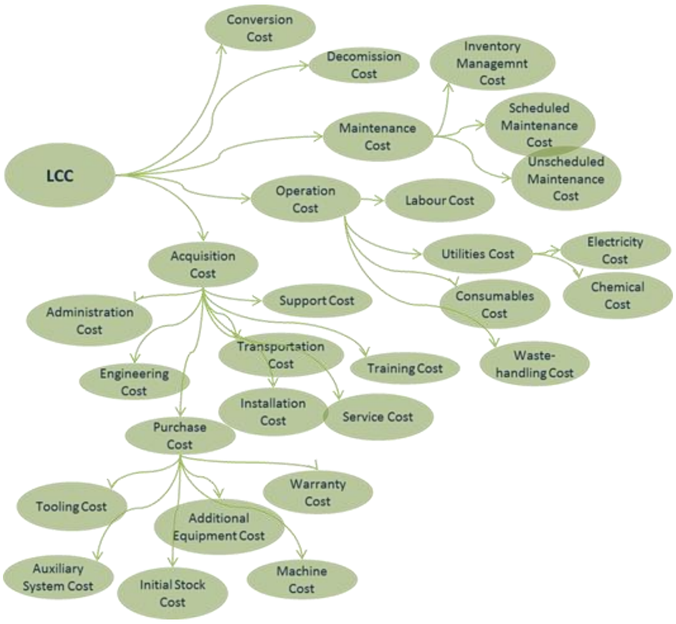


Fig. 8. Extract of the LD Ontology

The expressivity and completeness of ontology is performed through rules and axioms definition in order to capture the dynamics and semantic foundation of a domain [22]. They are considered as intentional knowledge or also explicit knowledge. Ontology rules and axioms are represented with logic languages, such as descriptive logic or first order logic [23]. Being machine understandable, ontology supports the deduction of implicit knowledge by processing logic-based rules using an inference engine. Rule inference engines chain several rules and provide us with more complex conclusions and hidden facts, resulting in more detailed, clearer model of the domain.

In the context of the Closed Loop Framework, LD ontology implements three types of reasoning: (i) testing of proposed line composition, against customer requests; (ii) calculation of characteristics of a production line, based on characteristics of the stations used; (iii) monitoring the performances of the line in the operational phase.

These three categories of reasoning involve mostly two different phases of the product lifecycle: the proposal (or concept) phase and the operational phase. The goal is to enable an automated calculation of the products LCC and to optimize the line configuration according to the costs and environmental impact. The base set of rules is implemented in SWRL (Semantic Web Rules Language) [22]. It is important to highlight that rule inference is self-initiated process. It is a background process on all levels for all the concepts that trigger a set of alarms to notify in a real time the main actors involved in the Closed Loop Framework (designer, IT experts, servicing). An extract of this base is given in Fig. 9.

If Customer.Availability > Product.AsDesigned.Availability then Alert.Active=1 and Alert.Text="Check Customer Required Availability" and Alert.Address="Designer"

If Customer.QualityIndex > Product.AsDesigned.Availability then Alert.Active=1 and Alert.Text="Check Customer Required Quality Index" and Alert.Address="Designer"

If Customer.DownTime < Product.AsDesigned.DownTime then Alert.Active=1 and Alert.Text="Check Customer Requested DownTime" and Alert.Address="Designer"

If Customer.Surface < Product.AsDesigned.Surface then Alert.Active=1 and Alert.Text="Check Customer Requested Surface" and Alert.Address="Designer"

Fig. 9. Extract of the base set of rules

4. Conclusion

In this paper the main aim is to show a closed loop framework, completed by tools, to improve life cycle performances of industrial systems. In detail, Section 3 presents the framework proposed (Fig. 2) and the different tools. The framework is the answer to sustainability need, driven by the structural changes that manufacturing industry is facing during the last years. It enables a holistic approach, allowing designers and system engineers in the collection of data from the field during the use phase, closing the loop with the design phase. The main benefits identified are: (i) to update existing database with data from the field, increasing the database accuracy; (ii) consequently, to improve the accuracy of life cycle costs and environmental impacts estimation during the concept phase; (iii) to understand the behavior of the manufacturing system during the entire life cycle, in order to manage in the better way the existing one and to improve the design of the next manufacturing systems.

Until the end of LinkedDesign project, next steps are the application of the framework on a real case or on a realistic case that simulate the system life cycle, testing the framework by the Italian automotive systems' company. After the LinkedDesign project, the next step would be to complete the framework, collecting and sharing data also in the end of life phase (conversion and/or decommission), in order to increase the effectiveness of design process about the life cycle performances of industrial systems, completing the holistic view.

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