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A Semantic Framework for Sustainable Factories

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Abstract

The world's energy consumption has doubled over the past 40 years and it is estimated that one-third comes from industry. Therefore, an increase of the efficiency in energy use in industries would greatly benefit the sustainability of the factories and consequently of the whole environment and society. A factory is a complex entity constituted by possibly networked plants which produce a set of products performing several processes requiring a set of production resources. All these aspects need to be considered as a whole especially is sustainability is of concern. However, this need implies the collaboration between several actors and tools having remarkably different competences and scopes. This paper presents a holistic framework, named Sustainable Factory Semantic Framework (SuFSeF), aiming at integrating digital models and tools to support the design and management of a sustainable factory thanks to its complete virtual representation. This framework extends the Virtual Factory Framework (VFF), outcome of a European research project, by characterizing the industrial building and considering energy and environmental sustainability of the factory during its lifecycle. Both commercial and prototypal software tools can be integrated in the framework. Specifically, the attention will be focused on tools to support the sustainability assessment during the factory design phase, 3D design tools, and the monitoring of the key energy-environmental indicators during the factory operating phase.

Keywords: Virtual Factory; Sustainable Factory; Data Modelling; Life Cycle Analysis

1. Introduction

The environmental and climate impacts of energy use are rapidly becoming a major issue. Carbon dioxide (CO_2), a major greenhouse gas, is emitted into the atmosphere directly when fuels are combusted on–site and indirectly when electricity is consumed (particularly when fossil fuels are used to generate electricity) [1]. The industrial sector uses more delivered energy than any other end-use sector, consuming about one-half of the world's total delivered energy and 30% of the total final energy [2]. Based on benchmark data, the current energy saving potential in manufacturing industry and petroleum refineries is estimated to be approximately 26% of the current total final industrial energy demand worldwide [3].

Energy is consumed, in the industrial sector, for a wide range of purposes, such as processing, assembly, producing steam, cogeneration, heating, air conditioning, and lighting in buildings. In particular, buildings (both residential and industrial) are responsible for approximately 40% of the total world annual energy consumption [4, 5]. Most of this energy is for the provision of lighting, heating, cooling, and air conditioning.

These data represent a strong motivation towards the design and management of *sustainable factories* aimed at reducing the energy consumption in the industrial sector focusing on the building as a key factor. The sustainable design and management of a factory may lead to the following benefits: (1) reduce the negative impacts on local environment; (2) reduce the resource consumption (energy, water and materials); (3) guarantee an adequate functionality level (optimal indoor conditions, adequacy of support structures and services); (4) reduce the management costs and (5) foster the harmonic development of the territory.

Both governments and scientific research community are paying an increasing attention to the topic of sustainability in manufacturing. As a proof of this effort, global and national research programmes have been launched, such as “Horizon 2020” in Europe [6] and “Sustainable Manufacturing Program” by the National Institute of Standards and Technology [7] in the United States.

Within the research community, many contributions can be found including sustainability to evolve existing design paradigms, related to product, process and production resource, under a sustainable point of view, as well as new approaches have been defined to improve the building efficiency [8, 9]. However, it must be noted that advances made in the *residential* construction field have not yet been fully exploited to support the *industrial* building design process that is characterized by specific requirements and constraints [4, 10]. The industrial building has been considered mainly as a container, whereas efforts for energy saving focus on the product/process optimization neglecting the building sustainability or treating it as separate to the manufacturing system [11]. A possible motivation for this lack can be brought back to fact that the environmental certification for industrial buildings is not mandatory in many countries in the world. Despite this, several proposals have been made, in different countries, for assessing the sustainability of industrial buildings.

Nonetheless, the lack of an integrated approach is evident, especially analysing the software tools resulting from the research in this area. Several tools supporting the sustainable design have been designed as well as tools for the evaluation of sustainability during the factory lifecycle [10], but these applications focusing on specific aspects and are typically used in a standalone manner thus hindering the possibility for other applications to exploit their results. As a result, despite their indisputable usefulness in supporting specific activities, they fail to provide an integrated solution for the sustainable development of the factory as a whole.

The use of different languages as well as different data formats (e.g. CAD representations, XML files describing objects in the factory, spreadsheet files) represents one of the most relevant causes for this lack of interoperability. This can be tackled developing a common environment where information generated by different tools and concerning the different aspects of the sustainable factory are modelled in an agreed manner that can be understood by *all* the software tools connected to the platform. If such an environment is available, tools can exchange information succeeding to provide an integrated suite covering several aspects of the sustainable factory.

This paper proposes such a holistic framework, named the Sustainable Factory Semantic Framework (SuFSeF), aimed at enhancing the interoperability between the methodologies and tools supporting the design and management of a sustainable factory, while as a reference the Italian Protocollo ITACA for the definition of the needed properties to characterize industrial buildings under the sustainability view point [12].

Section 2 will present an overview of the literature contributions related to the sustainable factory in the manufacturing domain. Section 3 introduces the SuFSeF framework, whereas section 4 delves into its main components. Section 5 describes the digital factory tools that are envisioned to be integrated in the platform, whereas section 6 presents the deployment of the framework through a demonstrator.

2. Sustainable Factory: literature overview

The sustainability of a factory can be assessed by evaluating the sustainability of its production systems, processes, output products, and building elements. These aspects are usually tackled separately as actors involved in the design and management of the factory work in a non-integrated manner, due to the different competences. This is particularly true comparing building and manufacturing systems [10]. If scientific research has been brought in the direction of integrating product, process and machine aspects thanks to similar engineering competencies (i.e. mechanical and automation engineering), only few results are available proposing the integration of the building aspects which are mainly related to architectural and civil engineering [4]. Furthermore, even if integrated, proposed approaches usually focus on a specific stage of the factory lifecycle (typically the design life stage). Moreover, the attention is usually focused on contamination caused by the production process or activity throughout the building lifecycle (air, noise, water) and process waste deposition and recycling, but little attention is paid to the building itself. However, the industrial building is permanently interacting with the other factory elements and the behaviour of a manufacturing system impacts the building sustainability and vice-versa [13]. The literature related to sustainability of residential buildings [14] could be exploited and extended to support the design and management of industrial buildings in the different stages of the building life cycle, from conception thereof, through its useful life, until the demolition stage and management of the waste generated.

Concerning products, the design activity plays a fundamental role as it defines the product environmental impact over its entire life cycle, i.e. any improvement in the product design process may affect the environmental performance [15]. Nonetheless, the evaluation of the environmental impact has been considered as central during the utilization phase together with materials, product function and the whole product system [16, 17, 18]. However, an integrated approach to estimate product impact over the manufacturing system has rarely been addressed [19].

Focusing on the process aspect, Croom et al. [20] investigated the relationship between innovative manufacturing techniques and environmental sustainability. Manufacturing processes consume resources directly and produce environmental pollution as well as being the main factors that affect sustainability [15]. Innovative studies on green manufacturing processes show promising results [21, 22].

The research on processes is strongly connected to production resources. Machine tool energy consumption may be reduced in one of four areas of its life cycle: manufacturing, transportation, use or end–of–life. Recent research includes power consumption analyses of machine tool use [23, 24].

The presented research led to and fostered the development of several software tools supporting specific tasks entailed in the design and management of a sustainable factory [15]. All these applications use data coming from the design and optimization activities (and related software tools) as well as information from the real factory. Nevertheless, as previously highlighted, there is a substantial lack of contributions dealing with the integration of building and manufacturing systems related knowledge and, as a by-product, with the integration of software applications. This represents a critical issue and challenge when dealing with the whole factory especially if sustainability is concerned. A result towards an integrated approach for the development of factories throughout their lifecycle is represented by the Virtual Factory Framework outcome of the European project VFF [25, 26]. The VFF represents a platform for software tools supporting design and management tasks throughout the factory lifecycle. Thanks to the presence of the VFF, integrated tools can access a common repository containing *relevant* information of the factory. Applications can download, modify and save data back into the common repository enabling other integrated tools to download and use the updated information [26].

3. Sustainable Factory Semantic Framework – SuFSeF

The SuFSeF framework adapts and extends the VFF to effectively and efficiently support the design and management of the factory considering both building and the related manufacturing systems while focusing on the energy and environmental aspects. The framework will support designers, production managers and analysts to independently and collaboratively work on a set of possible factory representations as well as on the real factory.

3.1. SuFSeF Overview

The objective of SuFSeF is to answer the need of an integrated approach to tackle the sustainability of the factory as a whole. Specifically, it aims at: (1) supporting the effective integration of the virtual representation of various factory components, such as the buildings and manufacturing systems; (2) facilitating the management of information related to energy and environmental performance (i.e. reduction of primary energy, reduction of GHG emissions, recovery of the thermal energy embodied in material and/or production waste) together with the production operations (i.e. reduction of scraps and material waste, optimization of usage and recycle of consumables, preventive maintenance); (3) supporting the exploitation of the best practices part of the company background; (4) supporting the increase of workers efficiency and safety; (5) facilitating the parallelization of tasks and management of distributed tools/information. In light of these objectives, the following steps can be foreseen guiding the framework development: (1) realization of a common language supporting building and sustainability definitions, which will lead to an extension of the VFDM [27]; (2) development of a knowledge repository; (3) development of new tools supporting sustainable factories design and management and integration of both new and already existing software applications within the SuFSeF platform.

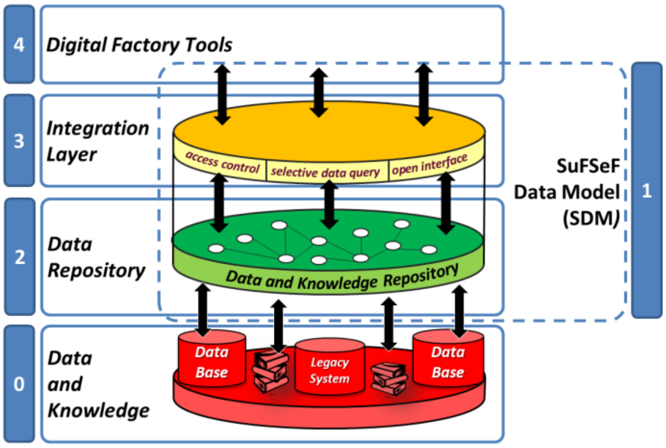

Figure 1: SuFSeF Architecture

3.2. SuFSeF Architecture

The SuFSeF architecture (Figure 1) guarantees the needed level of system reliability for the management of interactions and iteration loops. The framework will enable: (1) data consistency between several factory representations; (2) data exchange between several software applications accessing a common data repository; (3) traceability of the story of factory data revisions with possibility to retrieve old versions, revert modifications and create new working hypotheses.

In Figure 1, at the basis of the architecture, we have all the proprietary repositories owned by the company. At this level all the company knowledge is supposed to be stored in data bases and legacy systems (level 0).

At level 1 the SuFSeF Data Model (SDM) provides the common language to share the information contained at level 0 (proprietary data) and level 4 (i.e. the data coming from the Digital Factory Tools environment). As the SDM represents the common shared meta-language, it crosses several layers and it represents the fundamental enabler for the achievement of interoperability. The data model will have to consider many aspects of the factory during different life stages. As a result, many hypotheses of factory design will coexist at the same time each from a different life cycle phase, and a set of digital tools will access this information.

At level 2, the Data Repository (DR) will be responsible for storing the data and knowledge according to the SDM and provide access to it thanks to an integration layer (level 3).

At level 4, Digital Factory tools will be both new and existing software applications. These tools, usually based on internal proprietary data structures, will need the development of a dedicated *connector* that takes of I/O translation with respect to the common data model, thus enabling the platform integration.

4. SuFSeF Data Model and Data Repository

The data model, as a common language that can be understood by all the integrated applications, is fundamental to the digital factory tools and actors involved in the sustainable factory development to safely retrieve and store information. The data provided by each digital factory tool should be available to all connected objects wishing to download/update this information.

The SuFSeF Data Model (SDM) represents this shared meta-language providing the definition of the information that will be stored in the data repository and used and updated by the software tools (and actors using them) integrated in the framework [25]. To be effective, the SDM has to characterize the concepts of building, product, process and resource sustainability and their relationships. As it will be further detailed, the SDM will be developed as an ontology.

Once data have been formalized according to the SDM schema, an efficient way to store data provided/required by the applications connected to the SuFSeF platform is required. Three main approaches could be adopted: (S1) File System Based solution, requiring the ontologies to be serialized as files and stored on a local or remote repository; (S2) solutions based on relational databases where the ontologies are stored as tables; (S3) native stores for Resource Description Framework (RDF) [28] data that can be used also for ontologies by exploiting their representation as graphs. Based on the specific needs that arise, the best solution for the data repository can be chosen.

4.1. Data Model Requirements

The main requirements that must be satisfied, in order to obtain an effective platform for data exchange are: (1) covering relevant fields related to the Factory Domain, while focusing on the environmental aspect of building, resources and processes; (2) use of existing technical standards to foster the spreading of the SuFSeF solution; (3) semantic representation of data, i.e. the data model must embed the meaning of its instances. The description of how the stored symbols relate to the modelled system is made explicit using such a model; (4) extensibility, i.e. adding data structures will have to be always possible and will have to keep the data compatible with the previous versions. This requires a good initial conceptual model of the SDM basic architecture, so that it will be possible to immediately exploit the extensibility mechanism not only during the utilization of the model but also during the development phase.

4.2. Data Model Implementation Guidelines

The SuFSeF semantic data model will be based on the ontologies of the Virtual Factory Data Model (VFDM) developed within the VFF project [27]. Indeed, despite its generality, the VFDM still presents many open issues: (1) no detailed modelling of both building and resources information; (2) the concept of state dynamically changing over time is not formalized; (3) the performance measure concept was not defined and, more important, the connection between the performance measure and classes defined within the different domains was not designed.

In light of the first aspect, the VFDM will be advisably extended in order to include classes that characterize the building properties. Concerning the building, the Industry Foundation Classes (IFC) standard will be kept as reference as it was done during the development of the VFDM [29, 30]. Concerning the second aspect, the energy consumption varies dramatically based on the state in which the resource is (e.g. a machine energy consumption profile when it is idle, busy or failed). Since this aspect is fundamental for both environmental impact evaluation and sustainability assessment, the states need to be explicitly introduced. Both standards (e.g. Process Specification Language – PSL [31], Business Process Modelling and Notation – BPMN [32]) as well as formal languages (e.g. discrete event system specification – DEVS, Petri Nets [33]) are being investigated and it is envisioned that the final solution will merge both approaches.

Considering the third point, the concept of performance is fundamental in SuFSeF framework for two main reasons: the need to formalize the output coming from any digital factory tool and the need to formalize the environmental indicators describing the factory sustainability level.

To exemplify the extension activity performed, consider building elements such as *windows*, *doors*, *walls* etc. In the previous release of the data model, these entities were not detailed since this was not needed in the scope of VFF. However, these components are fundamental in case an assessment of the environmental and energetic efficiency of the factory need to be performed. Two extension directions were taken: (1) adopt IFC standard to detail the description of the structure of these components, (2) add new properties and restrictions useful to compute environmental indicators according to the Protocollo ITACA for Industrial Building [12]. Relating to the first point, and considering the *window* as an example, the layers and the materials adopted for each layer were introduced in the new release of the data model to fully characterize geometrical and physical properties of the entity. In the scope of the environmental characterization, some properties needed to be defined *ex-novo* since they were not considered in any of the adopted standards. For example, new restrictions in the ontology allowed modelling indicators such as the *average mobile shields use (FSH* indicator*)*, representing the weighted fraction of the time during which the solar shading is in use, and the *shadowing factor due to horizontal elements* (*HorizontalFin*), i.e. the fraction of effective incident solar radiation due to permanent horizontal elements shading the window (e.g. a balcony). These properties are fundamental to define, for each building window, the total solar energy transmittance (*gt*), that is then used to compute the ITACA indicator Effective average solar transmittance of window/shading components ([12], section 1).

5. Digital Factory tools

The digital factory tools will be characterized by heterogeneous behaviours and needs. Some of them will be existing commercial applications conveniently equipped with adaptation modules (i.e. *connector*, section 3.2) in order to interface with the Data Repository according to one or more of the proposed solutions (section 4), while some others will be newly developed and possibly designed as semantic applications, i.e. compliant with the language established through the SDM. Two main categories of software tools will be developed and/or integrated within the platform, each supporting one or more activities throughout the factory life cycle: (1) environmental assessment tools, (2) factory design tools.

Environmental assessment tools will be developed to automatize and support the sustainability evaluation activity based upon already existing environmental certification tools. In particular, the SuFSeF focus will be on building environmental assessment throughout its lifecycle. In particular, DOCET is a tool for computing the energy performance of residential buildings. It will be extended to deal with the specific characteristics and rules for industrial buildings and a *connector* will be realized allowing the integration with the framework. The Lifecycle Cost Performance (LCP) tool will be newly developed and will receive the information coming from the shop floor and/or the simulation output to compute the energy consumption and to derive the CO_2 emissions caused by the production system. PI-INDICATORS will be a newly developed tool for the computation of the sustainability performance indicators according to the Protocollo ITACA for Industrial buildings. PI-SHEETS will be newly developed for the assessment of the environmental sustainability level of factory building according to the Protocollo ITACA.

Already existing factory design tools will be integrated to support 3D visualization/design and discrete event simulation. In particular, the Onto-GUI is a Graphical User Interface for the visualization, modification and management of the data repository content. The Simulation tool evaluates the performance of the production system; in particular, the commercial simulator Arena will be adopted [34, 35]. GIOVE-VF is a 3D virtual and collaborative environment to support the factory design [36] that will be extended to graphically support users in the characterization of factory resources. The digital tools will be connected to the platform developing connectors, i.e. additional software layers mapping input and output information from/to the platform. Thanks to the connection to the platform, the users of the integrated applications will exploit the possibility to store and retrieve data from other software tools.

6. SufSeF Demonstrator

The proposed framework will be applied to two main industrial cases: the Pilot plant for remanufacturing and recycling of Printed Circuit Boards (PCBs) which was built in ITIA-CNR starting from 2011 [37], and the plant of the industrial company Ginko Srl producing doors and windows for both industrial and residential buildings.

The actors using the platform will be different: (1) Plant designer, (2) System designer, (3) Building designer, (4) Machine tool designer, (5) Plant responsible, (6) Facility manager, and (7) Energy manager. Each actor will use a subset of the software tools connected to SuFSeF based on the specific lifecycle phase and according to his own competencies (e.g. the building designer will use the design tools during the design phase as the facility manager might want to use the assessment tools in different phases).

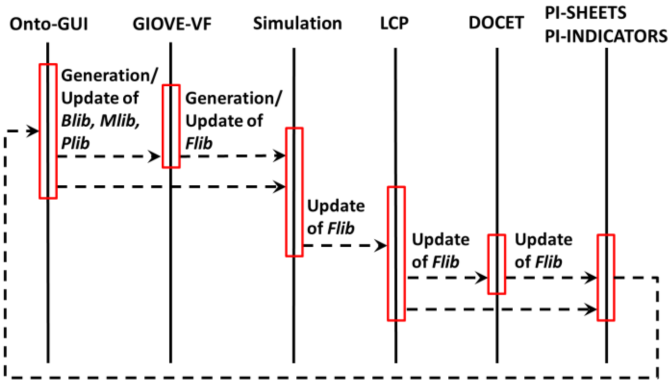

Figure 2: sequence of activities and information generated/modified

Three main activities which will be directly supported by the platform are: (1) Characterization of the plant and the manufacturing system contained; (2) Analysis of the energy and productive efficiency of the plant; (3) Industrial Building Sustainability Assessment.

Typically, the following data libraries will be developed: (1) Building library (*Blib*) where the building, its components and the service systems (e.g. heating, cooling lighting systems) are characterized; (2) Machine Catalogue (*Mlib*) containing the characterization of the machines that can be provided by machine tool builders; (3) Product library (*Plib*) describing the products produced within the plant together with the process plan(s) to produce them and the detailed process steps; (4) Factory Project (*Flib*) imports all the available libraries and defines the actual factory design, such as the number and placement of machine instances, the process assignments, etc. Moreover, each element in the factory project can be characterized with a performance history according to simulated or actual data. Figure 2 highlights the sequence of the supported activities and libraries created/modified by using a specific software tool

Once these activities have been performed, the analysis of the output from the plant responsible can lead to modify the configuration of the production system and/or the properties of the building. The modifications can lead to a decrease the productivity to favour the energy and environmental efficiency. PI-INDICATORS and PI-SHEETS can help the user in detecting the project elements that mainly affect the unsatisfactory performance indicators. This gives suggestions to the user on where to focus his attention in trying to reconfigure the plant (e.g. by adopting GIOVE-VF) for meeting the requirements, thus reducing the time spent by the user for modifying an existing non-satisfactory configuration and limiting the changes in the production volume. Then, by using the Simulation Module, the user can generate and run a new simulation model that considers the updated configuration. This improvement activity can be looped until a satisfactory solution in terms of productivity and sustainability is reached.

7. Conclusions

Starting from the analysis of the state of the art, this paper showed the structure of the SuFSeF platform, its objectives and how to reach them, by highlighting the proposed approach to integrate digital tools while aiming at designing sustainable factories. The preliminary results regarding the structure of the framework have been presented and the upcoming developments of the related research project were anticipated. The whole framework will be validated over industrial use cases.

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