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A Semantic Framework for Sustainable Factories

Walter Terkaj[a,]*, Ludovico Danza[b], Anna Devitofrancesco[b], Stefano Gagliardo[c], Matteo Ghellere[b], Franca Giannini[c], Marina Monti[c], Giulia Pedrielli[a], Marco Sacco[a], Francesco Salamone[b]

[a]ITIA-CNR, Via Bassini 15, Milano 20133, Italy
[b]ITC-CNR, Via Lombardia 49, San Giuliano Milanese, Milano 20098, Italy
[c]IMATI-CNR, Via de Marini 6, Genova 16149, Italy

* Corresponding author. Tel.: +39-02-2369-9607. *E-mail address:* walter.terkaj@itia.cnr.it

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,

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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