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An Ontology-based Framework for Sustainable Factories

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ABSTRACT

The problem of factory sustainability is commonly addressed by focusing on specific aspects related to products, processes or production resources, while the impact of the building and facilities is usually neglected even though it counts for 40% of the total world's energy consumption. This paper presents a holistic framework based on an integrated collaborative virtual environment that facilitates the sharing of the complete factory information and knowledge between various software tools, supporting the sustainable design and management of all the factory entities. In particular, the attention is focused on the Semantic Data Model that provides a semantic representation of the data and knowledge required for sustainability assessment.

Keywords: virtual factory, sustainable factory, ontology-based data model.

1. INTRODUCTION

Sustainable development is a relevant problem in European countries and all over the world; it requires considering environmental sustainability according to social and economic constraints. The world's energy consumption has doubled over the last 40 years and it is estimated that one-third of the global warming gas emission comes from industry [24]. Thus, for the sustainability of the factories, and consequently of the whole environment, it becomes of outmost importance to increase the efficiency in energy waste in industries. The optimization of the industrial production in terms of energy consumption and pollution reduction has to consider both manufacturing processes and building behavior by encouraging the use of alternative energy (see Horizon 2020 objectives) and improving indoor environmental comfort of the workers. This need asks for the design and management of the factories as a whole. The evaluation of the sustainability of a factory requires considering several components such as production systems, process, products, as well as building and services. However, these aspects are usually addressed separately, as they require different competences [21]. Only few results proposing integrated approaches are available, and they are mainly related to architectural and civil engineering and mostly focused on the design lifecycle stage [19]. In particular, to the knowledge of the authors, no approach looks at the energy and environmental aspects due to process and production, which are significantly related to industrial buildings and not to civil ones.

Several works address the evaluation of the environmental impact of a product over its entire lifecycle [2],[10],[16]. However, an integrated approach to estimate product impact over the manufacturing system has rarely been addressed [12]. Croom et al. [7] focused on manufacturing processes and investigated the relationship between innovative manufacturing techniques and environmental sustainability. Recent studies on green manufacturing processes with promising results may be found in [1], [14].

Different tools are available in the market to support the factory lifecycle, from the design to the construction up to the operating phase; unfortunately, these tools often fail in interoperability, either because they adopt different programming languages and platforms, or because they use different terminologies to describe the same domain or even same terms with different meanings. This lack of interoperability results in not fully satisfying customer requirements, being inefficient and missing opportunities to gain competitive advantages. Furthermore, even when commercial integrated suites are available providing a

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set of services, the resulting cost is unaffordable for small and medium companies. In addition, even when tools for assessing the environmental sustainability of buildings are already available, these are mostly developed to meet the market requests and technical regulations of a specific country. This means that they use different knowledge and data, as different assessment methods and tools are used in the various countries to assess sustainability of industrial buildings (e.g. BREEAM for United Kingdom [3], LEED for the U.S.A. [17], CASBEE for Japan [6], DNGB for Germany [9], Protocollo ITACA for Italy [13]).

A research result proposing an integrated approach for the development of factories throughout their lifecycle is represented by the Virtual Factory Framework (VFF), implemented during a European project [15,23]. The VFF is a software platform based on the Virtual Factory paradigm that supports design and management tasks throughout the whole factory lifecycle, allowing the access through integrated tools to a common repository containing relevant information about 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. The VFF represent a first step in the direction of enabling the integration between actors/tools throughout the factory lifecycle. However, this work did not focus on sustainability aspects and the building characterization.

The Italian funded project Sustainable Factory Semantic Framework (SuFSeF) [8] aims at extending the Virtual Factory Framework to include data and processes necessary for the energy and environmental assessment, thus supporting the sustainable design and management of all the factory entities.

The remainder of the paper is organized as follows: section 2 gives an overview of the data and knowledge required for factory sustainability assessment; section 3 illustrates the proposed semantic framework; section 4 focuses on the Semantic Data Model that makes available all the knowledge required to perform factory sustainability assessment; section 5 gives a brief description of the scenarios for validating the data model and section 6 concludes the paper.

2. ANALYSIS OF THE REQUIRED ENERGY AND ENVIRONMENTAL DATA

The sustainable factory concept entails the analysis of several areas. The main areas are: building, product, process and production resource. Each of these aspects is complex by itself and it is even more challenging when sustainability is considered (Fig. 1.). In particular, this aspect introduces additional relationships between different areas. In the following, the focus is on building aspects, as the building, hosting products, processes and production systems, represents by itself a complex aspect to consider in dealing with sustainable factories.

The energy and environmental analysis should be made during each of the main lifecycle phases of the building:

- design phase, where the factory building is not existing;
- construction phase, where the factory building is existing but not functioning;

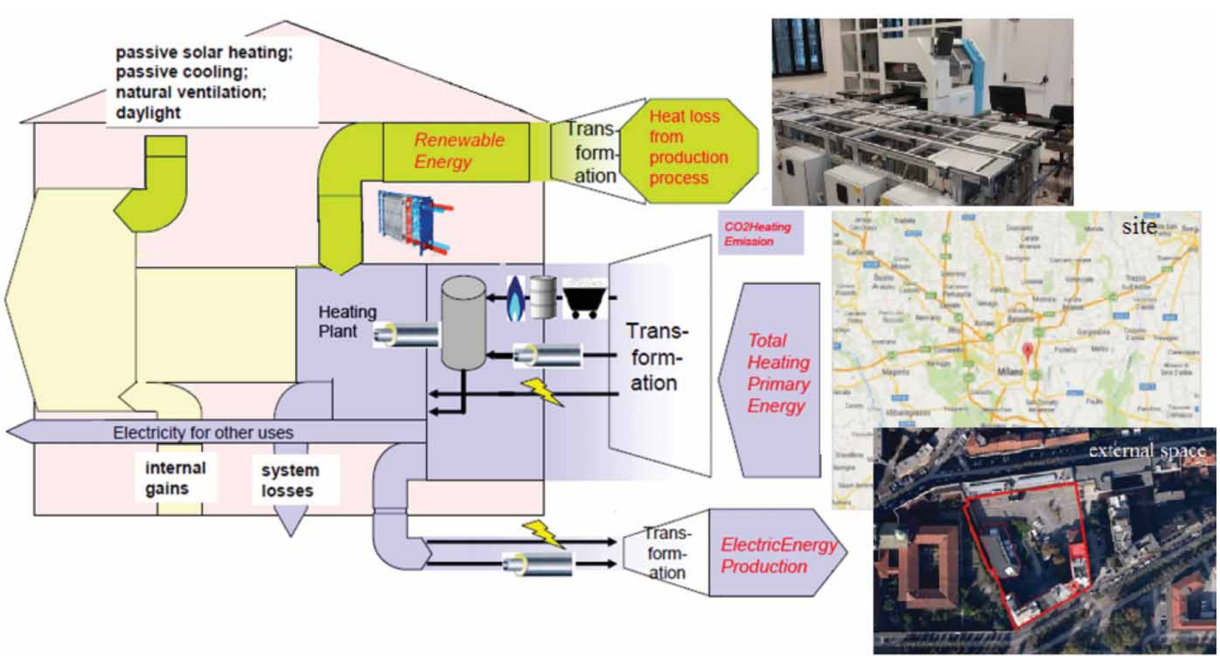

Fig. 1: Energy and environmental aspects in industrial buildings (Pictures from Google Maps - ©2014 Google).

- operating phase, where the factory building is existing and functioning.

At each phase, a different energy and environmental analysis is carried out, influenced by the source data available and usable for this scope.

At the design phase, the energy and environmental analysis determines a full theoretical sustainability performance of the building; on the contrary, in the operating phase the energy and environmental analysis is accomplished on real sustainability performance of the building. In the construction phase, a mix of the data is available and therefore some evaluations are based on theoretical data and some others on real ones.

While the data needed as input for energy and environmental analysis vary in relation to the considered lifecycle phase, as illustrated in Fig. 2, the output data are always of the same type. There are three kinds of output:

- Environmental sustainability indicators (ESI): physical quantities or building description that represent the building's sustainability performance about a specific aspect and measure unit.
- Environmental sustainability scores/credits: ratings linked to Environmental Sustainability Index (ESI) that evaluate the sustainability level of the building w/o measure units.
- Evaluation report: document that summarizes the energy and environmental sustainability assessment activity.

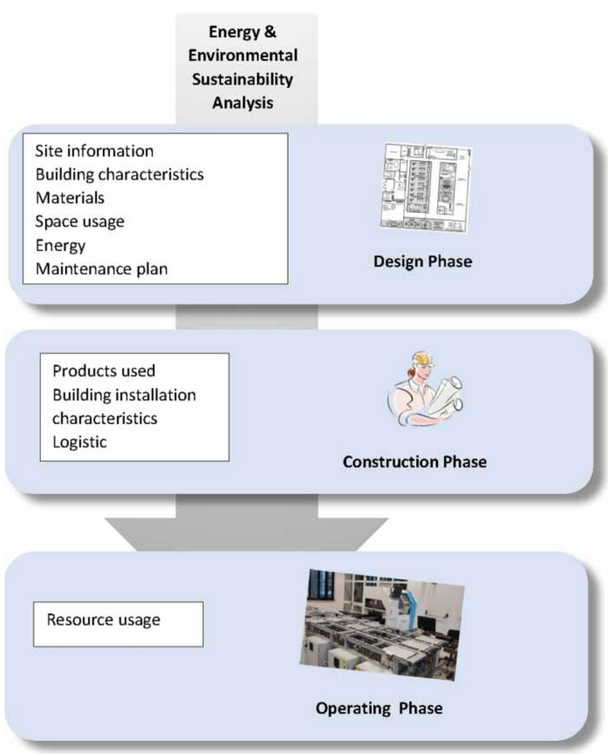

Fig. 2: Data considered in the energy and environmental sustainability evaluation in the different building lifecycle phases.

The sustainability assessment activity is executed with the use of support tools that have similar functionalities even if applied during different building lifecycle phases. The most used tools can be categorized in:

- Documents analysis tools: allow the verification of work conformity to design through the registration/validation of documents' checklist and could be configured as documents' registries.
- Performance indicator tools: implement the calculation methodologies of environmental sustainability indicators according to the assessment methodology used.
- Indicator normalization tools: allow converting performance indicators to environmental sustainability scores or credits according to the assessment system used.
- Text editors: allow producing the assessment report.

The definition of the energy and environmental sustainability level of the building follows different specific analysis.

In order to structure the required input data, a first subdivision between two general typologies of data can be made:

- Energy data: both data related to the building (either of the overall or of its components) and to the context that are used for energy consumption/production calculation.
- Environmental data: both data related to the building (either of the overall or of its components) and to the context (geographic and urban) that are used for industrial building environmental analysis.

The assessment of energy performances of industrial buildings can be conducted in a simplified manner using a small but significant number of data, which can be divided into three categories:

- Climatic context data: climatic characteristics of the geographical site in which the building is located.
- Thermal envelope data: geometric and thermal properties of the elements that delimit the building physically and thermally.
- Plant systems data: technical characteristics and specific properties of plant components that provide or produce energy for the building.

Climatic context data pertain to climatic data necessary for the energy analysis, including the external reference temperatures (monthly averages) and the values of solar radiation. In particular, the values of solar radiation of reference (monthly averages) are specifically required for all cardinal directions (main and intermediate) and the horizontal plane.

Thermal envelope data are necessary to know which elements disperse heat, as well as their physical characteristics. In particular, for each element (wall, window, roof or door) it is necessary to know its surface area and its thermal transmittance (U). Depending on the software used and the specific case, this last value can be determined by using the simplified method exploiting predefined U-values associated to the type of building element, analytically through the characteristics (thickness, thermal conductivity - λ) of the various layers that make up the elements of the envelope or by direct input. The heat transfer by transmission includes the calculations of linear and point thermal bridges according to simplified/detailed methods defined by the UNI/TS 11300-1 that represents the national reference for the application of the EN ISO 13790:2008. For the transparent components, such as the windows, it is also necessary to know the glass solar transmittance (g) and the presence, position and the material properties (i.e. solar transmittance, absorption, reflection) of shading elements. As for thermal transmittance U, also the window solar transmittance can be determined in a simplified manner by knowing the type of glass used (number of layers and filling gas) and the shading element position, color and material.

Plant systems data are related to the components for energy generation. The related data vary depending on the type of plant subsystem considered (emission, regulation, distribution or storage subsystem) and the generators typology (boiler, heat pump, solar).

Compared to the energy analysis, the environmental analysis for industrial building requires more complex data. The complexity is due to the fact that the non-energetic performance requested by the different systems is not homogeneous. This implies that the specification of the data required for environmental analysis strongly depends on the evaluation system considered. Therefore, the set of data that satisfy the needs of a selected evaluation system could be not sufficient to make an assessment using other evaluation methods or systems. This is because different methodologies, even if providing similar assessments, may use different rules and formulas applied to different operands.

In this research work, the specification and structuring of the data necessary for the environmental and energetic performance analysis of industrial buildings has been defined starting from the analysis of the methodologies and indicators specified in Protocollo ITACA [13], that is the assessment protocol used in Italy for energy and environmental sustainability for industrial buildings. In order to generalize the applicability of the framework, compliance verification has been carried out with respect to the other methodologies used in the various countries. Thus, the data considered to be formalized in SuFSeF Framework are not exclusively linked to Protocollo ITACA, but correspond also to the input requested by the other industrial buildings rating systems.

Input data for sustainability assessment may be organized in macro categories linked to the main elements that characterize an industrial building, which are:

- **Site**: data related to the whole area where the building arises (e.g. site distance to infrastructures).
- **Building:** data related to the building as a whole (e.g. number of users, primary energy need).
- **External Space**: data related to areas external to the building (e.g. permeability ratio of covers).
- **Internal Space**: data related to internal spaces of the building (e.g. daylight factor).
- **Envelope:** data related to building elements that thermally limit the building (e.g. thermal transmittance).

To achieve a more detailed structuring of the needed input data for indicators calculation, a thematic grouping is provided for the data of each macro area:

For the **Site**:

- Site selection: data related to the placement of intervention area, in particular to its geographic and social context.
- Site Project: data related to the general design of intervention area.
- Water: data related to water consumption for non-indoor use.

For the **Building**:

- Climate: climate data used for energy calculation purpose.
- Geometry: data related to building physical dimensions.
- Use: data related to building usage.
- Energy: data related to energy use within building.
- Management: data related to control strategies for functioning and building performances.

For the **External Space**:

- Geometry: data related to outdoor spaces' physical dimensions.
- Use: data related to outdoor spaces' use.

- Environmental loadings: data related to outdoor spaces contribution for environmental impacts reduction.
- Vegetation: data related to presence and type of green elements.
- Water: data related to potable water use in outdoor spaces.

For the **Internal Space**:

- Geometry: data related to indoor spaces' physical dimensions.
- Use: data related to indoor spaces' use.
- Lighting: data related to lighting properties of considered indoor spaces.
- Indoor comfort: data related to indoor spaces comfort conditions.

Concerning the **Envelope**, different groupings are identified according to the envelope element types, which are **Wall**, **Roof, Floor**, **Door** and **Window**; for each Envelope element type the related data are grouped in categories as well. For example, for the **Wall** and **Roof** elements relevant data are:

- Boundary space: data related to the external bordering environment.
- Geometry: data specifying the element's dimensions.
- General: data about the usage and the reuse of the element.
- Thermal: data about thermal properties of the elements.
- Layers and materials: data about used materials and layers.

Tab. 1 illustrates a subset of the data required to characterize some building aspects necessary for the sustainability assessment.

3. OVERVIEW OF THE SUFSEF FRAMEWORK

The SuFSeF framework considers various software layers allowing the access of modeling and evaluation tools to proprietary data through the use of a reference semantic data model. In particular, this framework provides:

- shared and extensible factory Semantic Data Model (SDM) formalizing information to describe the characteristics of site, building, product, resources and processes performed within the factory;
- enablers for the connection of software tools to the framework (both commercial applications and tools developed during the project), supporting factory design and management throughout its lifecycle;
- synchronization between the virtual and real factory for monitoring purposes;

The SuFSeF architecture (Fig.3.) guarantees the needed level of system reliability for the management of interactions and iteration loops.

At the lowest level, all the company knowledge is supposed to be stored in data bases and legacy systems. The SuFSeF Semantic Data Model provides the common language to share this information given by proprietary data and data coming from the Digital Factory Tools environment. The SDM represents the common shared meta-language that crosses several

Building data		
Type	Data	Measure
Climate	dispersive thermal envelope Surface/gross building Volume heated	Real
Geometry	Footprint area Gross floor area Net floor area Gross volume	m^2 m^2 m^2 m^3
Use	CO_2 Heating Emissions BAC factor weighted on heating/cooling EAC factor weighted on electric consumption Water consumption	Kg(C02) Real Real kw/h
Energy	Total heating primary energy Total cooling net energy Electric energy production Renewable energy use	kW/h kw/h kw/h kw/h
Management	Maintenance strategies Ccnstruction method	String String

Tab. 1: Building data.

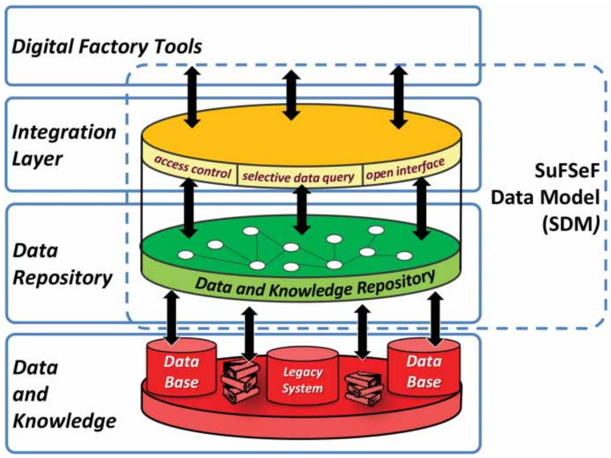

Fig. 3: The SuFSeF architecture.

layers and the fundamental enabler for the achievement of interoperability. The data model has to consider many aspects of the factory during different life stages. As a result, many options of factory design may coexist at the same time, each from a different lifecycle phase, and a set of digital tools can access this information.

The data and knowledge defined according to the SDM are stored in the Data Repository (DR), which provides access for the digital factory tools thanks to an integration layer.

Digital Factory Tools can be both newly developed tools and existing software applications. Among them, the existing commercial applications, which are usually based on internal proprietary data structures, need the development of a dedicated adaptation module in order to interface with the DR. The newly developed tools will be possibly designed as semantic applications, i.e. compliant with the language established in 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 lifecycle:

- environmental assessment tools to automatize and support the sustainability evaluation activity based upon already existing environmental certification tools;
- factory design tools to support 3D visualization/design and discrete event simulation [11,20].

Part of the tools required for the whole framework implementation have been identified and their development and/or integration is in progress. Specific connectors, i.e. additional software layers mapping input and output information from/to the platform, will be developed to integrate the tools in the framework. Thanks to this connection, the users of the integrated applications will exploit the possibility to store and retrieve data generated by other software tools.

4. THE SEMANTIC DATA MODEL

The SuFSeF Semantic Data Model provides a semantic representation of the data and knowledge required for sustainability assessment. The identification of these data and knowledge is the result of a long and complex process based on the analysis of the criteria, rules and procedures adopted for the sustainability assessment. The analysis is not trivial since a lot of heterogeneous knowledge and data are essential to carry out a full sustainability assessment [18], as it involves various and very different aspects such as energy, water and material use, urban configuration, comfort of indoor spaces and management. This variety requires the use of different document sources, which also depend on the specific phase of the building lifecycle.

4.1. The Data Model

The data model is developed as a set of interconnected ontologies, adopting the Semantic Web technologies. The Semantic Web technologies offer, indeed, the possibility to represent a formal semantics, to efficiently model and manage distributed data, to ease the interoperability of different applications, and to exploit generic tools that can infer from and reason about an ontology, thus providing a generic support that is not customized on the specific domain.

The SuFSeF semantic data model is based on the ontology set of the Virtual Factory Data Model (VFDM) developed for VFF [22], which exploited as much as possible already existing technical standards for manufacturing to provide an holistic view of the factory, from the building to the manufacturing process, facilitating the interoperability between software tools. Starting from the integration of various knowledge domains represented by different technical standards, VFDM then focused on the extension of the standards themselves and on the development of novel data structures. In particular, the following technical standards were considered: Industry Foundation Classes [5] for modeling the factory building and the most abstract classes of objects, and STEP-NC [25] for the manufacturing processes.

Despite the generality of the approach, the VFDM presents some limitations to meet our requirements:

- Detailed modeling of both building and resources information. In light of this first aspect, the VFDM needs to extended in order to include already existing classes from the IFC standard that were not taken into account in previous projects.
- The resource state concept still needs to be formalized within the data model; energy consumption varies dramatically depending on the state in which the resource is (e.g. idle, busy or failed); since this aspect is fundamental for both

environmental impact evaluation and sustainability assessment, the states need to be explicitly introduced, extending the VFDM ontology.

Moreover, the performance measure concept is not defined and, even more important, the connection between the performance measure and classes defined within the different domains was not designed.

Then, the data model implementation required two main activities:

i. Extend existing VFDM classes: the class of interest is already present within the VFDM, but further attributes/restrictions need to be added;
ii. Create new classes: the class is not present within the VFDM and the model needs to be extended.

In both scenarios, two situations can occur: the class to detail/add can be modeled following a predefined standard or introducing novel definitions.

Within this work, the decision to follow the IFC standard whenever possible has been taken, and only in case the needed information was not present in the standard novel definitions have been introduced.

4.2. The Extended Virtual Factory Data Model

With the purpose of covering all those characteristics suitable for energy and environmental sustainability assessment, VFDM has been extended by adding a new ontology, named SuFSeFFactory ontology, that in turn imports three different ontology modules, each one extending a specific area of the original VFDM related to materials, spatial elements and building elements (see Fig. 4.).

All the new modules, as well as all of their classes, have a prefix "SuFSeF" in order to distinguish them from those derived from IFC (prefix "Ifc") and those inherited from VFDM (prefix "Vff").

To model data linked to the various elements characterizing the building, summarized in Section 2, classes and properties are used.

Before proceeding to the ontology creation, a careful analysis of the classes already existing in the IFC standard and in the VFDM has been carried out. It turns out that most of the classes required are already considered in IFC, whereas most of the required associated data are not modeled in it, thus requiring an extension of the IFC property sets for these classes. Property sets are container classes that hold properties for specific object types.

To preserve the compliance to the standard and the original design of the existing VFDM classes derived from IFC standard, it has been chosen to

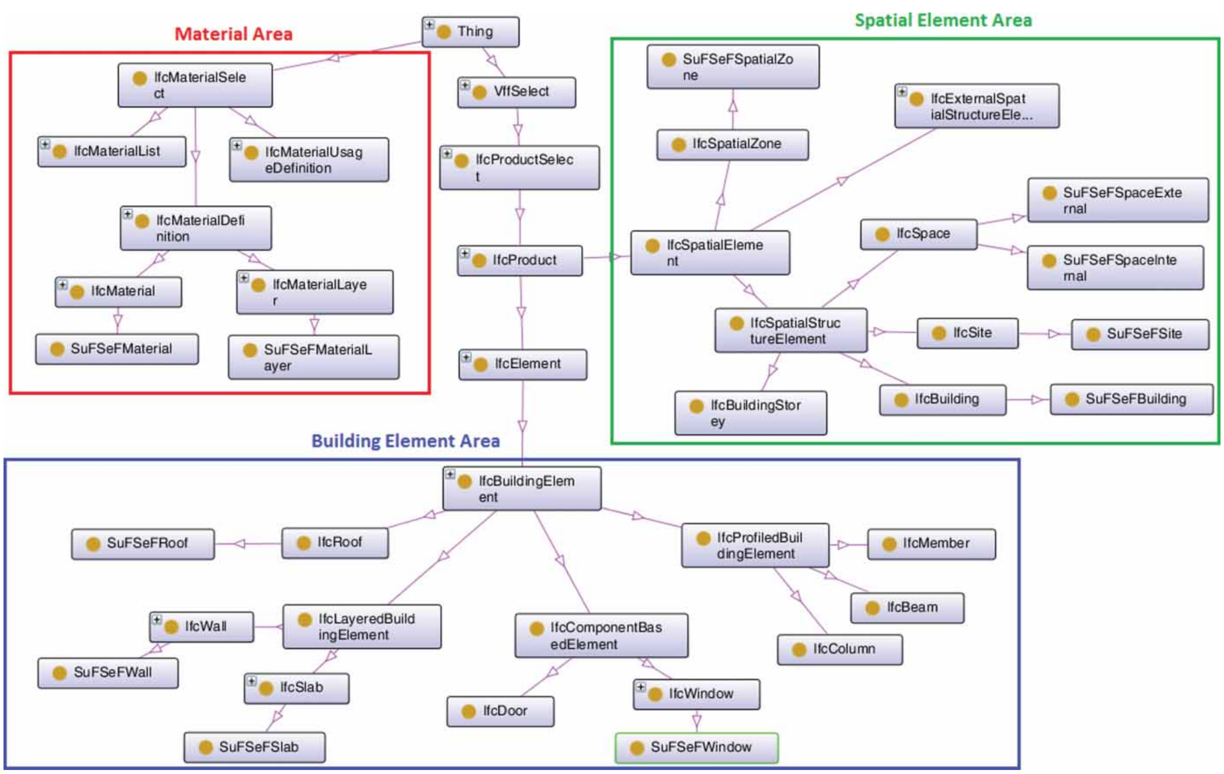

Fig. 4: An excerpt of the SufSeF Semantic Data Model representing the extension to the VFDM.

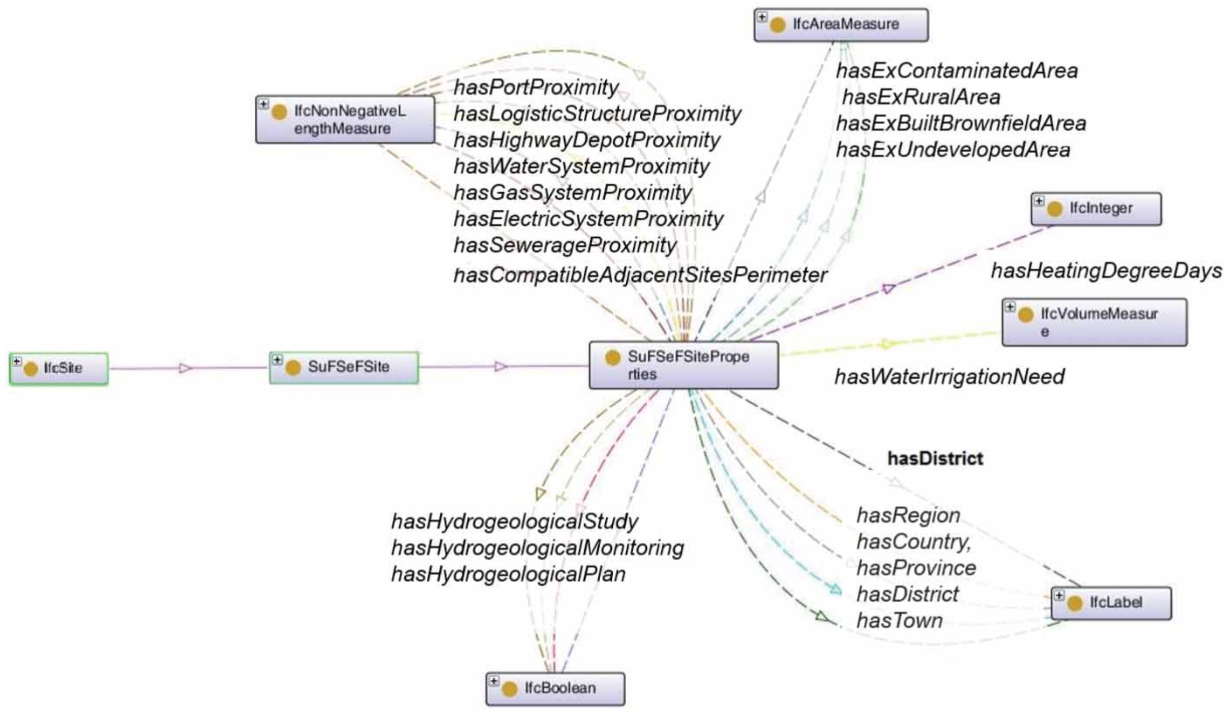

Fig. 5: The SuFSeFSite class.

create a SuFSeF class as subclass of the corresponding VFDM/IFC one each time a property needs to be added to an existing IFC entity. The classes are created in the corresponding module.

Data are then modeled as properties associated to the class representing the entity they refer to. When a property already existing in the IFC standard is applicable to a SuFSeF entity, then it is reused and accurately documented. Non-existing properties have been created and all the properties referred to an element are grouped in property sets corresponding to the class they refer to. Properties applicable to several classes are grouped in atomic property sets, which are used as super-classes of the property sets of the related classes.

Fig. 5 illustrates the class SuFSeFSite, created as subclass of the corresponding IFC class IfcSite, and its formalized properties created and grouped in the SuFSeFSiteProperties property set.

The entities and relationships within the data model (i.e., within all the ontologies of the data model) are defined according to the OWL 2.0 language and the ontology editor Protegé 4.3 was used to create all the classes, restrictions and properties.

5. DATA MODEL VALIDATION

Two scenarios for validating the SuFSeF framework were identified. The first is the De-manufacturing Pilot plant at the Institute for Industrial Technologies and Automation of Italian National Council for Research in Milano (Italy), a factory meant for disassembling, re-manufacturing, recycling and re-using of Printed Circuit Boards (PCBs) [4]. The second is Ginko Srl Production Plant in Origgio (Varese, Italy), a factory initially focused on the production of all types of aluminum doors and windows that, since the mid-90s, has become specialized in the production of armored frames in aluminum for both industrial and residential buildings. Three main activities are going to be supported by the platform:

- the characterization of the plant and of the manufacturing system contained in it;
- the analysis of the energy and productive efficiency of the plant;
- the industrial building sustainability assessment.

Taking as an example the test case of the De-manufacturing plant, four ontology libraries have been created:

- design the number of ontologies needed for each case and import relationships between them;
- identification of the needed entities/relationships and related restrictions;
- population of the ontologies, i.e. creation of the individuals for the needed entities.

Taking as an example the test case of the De-manufacturing plant, four ontology libraries have been created:

- a building library (RdmLibBuilding), where the building is described in terms of its characteristics (e.g. production site, internal and external spaces), components (e.g. walls, windows, roofs) and its service systems (e.g. heating, cooling and lighting systems);
- a machine library (RdmLibElement) containing the 3D model machine characterization that can be provided by machine tool builders;
- a machine type library (RdmLibElementType), that types the elements in the machine library;
- a product library (RdmLibProduct), where the products produced within the plant are described together with the process plans needed to produce them, whose steps are already detailed.

A factory project ontology named RdmPlant02 imports all the just introduced libraries, thus representing the descriptor of the whole factory data. Dividing the whole factory into modules, the data distribution empowered by the semantic web approach is exploited. In this way, each of the libraries focuses on specific aspects of the factory that can be possibly populated or extended by experts in different areas. Moreover, some data, like machine data, can be useful on their own and the ontology separation allows users obtaining them in a more efficient way and without being locked by some other data.

The data formalization confirmed that the expressivity of the extended data model allows the characterization of all aspects required as input by the tools designed for the energy and environmental sustainability of the chosen test cases.

6. CONCLUSIONS

This paper illustrates the SuFSeF platform, its objectives, the innovative approach and the idea of the sustainable factory as a whole set of aspects whose integrated analysis is a key factor. In particular, the paper focuses on the developed semantic data model and illustrates the knowledge it provides.

The data model represents a common language that can be understood by all the integrated applications and allows digital tools and actors involved in the sustainable factory development to safely retrieve and store information.

As the different existing assessment protocols mostly start from a common set of data but often use different evaluation procedures, the data model includes all those data that are commonly required by sustainability assessment tools, leaving to the tools themselves the computation of those data that are evaluated starting from the modeled data.

Two test cases are used to check its validity in adequately expressing all the knowledge necessary to the different tools that are used for planning and monitoring the different phases of a factory lifecycle, taking into account environmental and energy sustainability. Further extensions of the data model involve the modeling of the data necessary for the sustainability assessment of industrial plant in working conditions.

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