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An approach to support I4.0 adoption in SMEs: a core-metamodel and applications

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Abstract: Despite the recent growing interest in the “factory smartness”, still there are few small and medium enterprises (SMEs) that adopt effective I4.0 solutions. The main reasons can be related to the lack of formalized processes, lack of ICT knowledge as well as low-cost commercial systems. To cope with these issues, this work focuses on the development and the application of an approach to provide SMEs with a multi-purpose, modular, knowledge-based system: the main aim is to provide a modular and extensible system that can be incrementally implemented without requiring a huge initial investments. This system is based on a core design-knowledge metamodel. From this core metamodel, multi-purposes *modules* can be built: in this paper, we present modules for the traceability support, the AR-powered assembly support, the machine-to-machine control and the data analysis support.

Keywords: knowledge-based systems, Industry 4.0, SME, multi-purpose systems, modular systems.

1. INTRODUCTION

The recent growing interest in the “factory smartness” related to the availability of high-performing low-cost information and communication technologies give the chance to rethink the old concept of manufacturing operations. The core of the Industry 4.0 (I4.0) is an announced revolution (Kagermann et al., 2013) in the potentialities of predicting the manufacturing outcomes by the profound knowledge of the processes available. The potentialities of I4.0 lie then in a better flexibility and scalability of manufacturing systems through information technologies and industrial automation (Brettel et al., 2014; Dassisti and De Nicolò, 2012). The “support wave” of a number of governments all around the world for I4.0 solutions is forcing this paradigm change, with a debatable success (e.g. Industrie 4.0, Manufacturing USA, Industrie du Futur, Industrial Internet of Things, Made in China 2025, Fabbrica intelligente-Industria 4.0) (Issa et al., 2017). The funding action is in fact unnaturally pushing the change, thus hurrying adoption of implementation solutions not adequately structured or even needed. The proof of this is that still few companies, particularly Small and Medium Enterprises (SMEs), are keen to adopt truly I4.0 solutions (Bosch, 2015; European Commission, 2015; Federmeccanica, 2016; Ubisense, 2014). If SMEs cannot align to I4.0 solutions this can seriously affect the economic growth of a country (Kagermann et al., 2013; TELUS and IDC, 2014; Ubisense, 2014). SMEs tend to overestimate the complexity of I4.0 solutions and to underestimate their benefits mainly because they believe that the I4.0 is a fad not suitable to them. In fact SMEs are often characterized by poorly formalized processes, by independent and/or legacy hardware and software systems and by smaller economical resources (against the large companies). Furthermore, they typically lack internal IT competences and the related technological knowledge. Starting from this scenario, this work answers to

the following question: *how it could be facilitated the adoption of I4.0 solutions by SMEs?*

2. THE NEED OF A CORE-METAMODEL

To address the question put in the Introduction, several steps are required: an amazing simplification of the I4.0 system creation to extend their use to different knowledge domains (Bosch, 2015); a gradual introduction of the new technologies without ask to the SMEs to have large investments to replace the existing systems (Federmeccanica, 2016); to make the use of the I4.0 solutions user-friendly (Bosch, 2015); to provide a simple and total interoperability with the existing legacy systems. The so-called Cyber- Physical Systems (CPS) refer to the combination of and coordination between the physical assets and their computational capabilities. These hardware and software components are deeply intertwined interacting with each other in diverse ways that change with context. Still this recognition does not provide the satisfaction of the following two main requirements for a SME-oriented I4.0 solutions (SMEI4.0):

- *knowledge-based*: minimize the need of expert work to integrate the different interfaces that are intended to cover the I4.0 requirements;
- *extensible*: SMEI4.0 solutions must be flexible to allow a gradual implementation. They must ensure the possibility to reutilize the entire systems if other components are to be added.

The last requirements can be met only with a core-data model to be reused in all I4.0 application: a kind of metamodel for the knowledge representation of the “I4.0-enterprise”. A similar need has already be expressed in the MIT *Solid* project (Mansour et al., 2016): split the application and the used data.

In our industrial scenario, this means having one core-metamodel and different application gravitating around it with different aims. In other words, each application has a common database. For a clear description of complex concepts, it is already clear that adequate reference models are required. Amongst all, cited in (Thoben et al., 2017), we mention the need of further research on “advanced knowledge representation mechanisms, supporting stakeholder communications and strategic standardization across manufacturing”.

Different studies tried to address these issues. For instance, in (Harrison et al., 2016) propose the “vueOne” development environment to implement a cooperative platform SME oriented. The system proposed is based on a common knowledge model that supports all the activities along the product life cycle. In (Huang et al., 2013) the idea of manufacturing resource and capability sharing based on cloud computing for SME is faced introducing a SME-oriented cloud manufacturing service platform. This cloud-manufacturing platform is a momentous tool to exploit and share the manufacturing resource, promote design of products, operation management, and manufacture ability, and enhance the comprehensive abilities for the SMEs. The model behind this approach is by layering the architecture and clustering resources within each layer by interfacing them using transaction agents. Still it is a prototype platform that has to prove the flexibility to self-adapting to varying conditions, provided no knowledge sharing model has been adopted. The center of the cloud-manufacturing model is always knowledge (Tao et al., 2011) with its layering approach that supports the servitisation of each manufacturing steps, always relying on an appropriate platform: from design up to maintenance and integration. Finally, in (Schlegel et al., 2017) the new approach «Linked Factory» developed by Fraunhofer Institute for Machine Tools and Forming Technology is discussed. This approach relies on a common hub sharing knowledge and data. The problem highlighted is, however, that collected data is mostly used and analyzed only accordingly to the original reason of acquisition. A crucial aspect, the common available production-related data often contains hidden interdependencies that are relevant to manufacturing. This interesting point stresses again the missing of an adequate and general modelling of the manufacturing scenario.

Despite the number of technical and scientific works facing the adoption of I4.0 solutions by the SMEs, none of these works clearly states a final solution of how the above mentioned requirements can be practically addressed. In the next sections, we propose the extension of a knowledge model based on the concept of *measurement*. The aim is to put it as core model for the I4.0 scenario for SMEs.

3. A CORE-METAMODEL FOR I4.0 APPLICATIONS IN SMES

Since the I4.0 principles are about automations and M2M (machine-to-machine) interaction, the knowledge formalisation framework should be able to represent the sensors capabilities and to make action on machine’s actuators. So, it is necessary a core-metamodel to formalise the

knowledge of experts and minimizing the integration issues. This matter has been faced in (Giovannini et al., 2015): here the authors propose a conceptual framework to formalise the knowledge to minimise the ambiguities.

3.1. Concepts of the knowledge formalisation based on measurements

The conceptual model showing the basic concepts of the framework in (Giovannini et al., 2015) is in Fig. 1 (blue classes and black relationships). This framework was intended to formalise design knowledge to minimise the ambiguities. In the same paper, the authors use the concepts of *measurement* to limit the ambiguities (i.e. a content is subject to more than one interpretation) when several modellers instantiate the knowledge-base. In other words, the disambiguation is based on the measurement system, i.e. the unit of measure, the range of measured values, the error, the time and place of measurement. The semantics of the main concepts in the proposed framework is the following.

A *measurement* is the characterisation of the act of perceiving. This concept can identify a sensor with its time and place of measurement. For instance, the temperature perceived in a sensor positioned in a volume of air at a time t .

A vector with *space*, *time* and *shape* (S, T, S) characterises each measurement. For instance, the temperature can be the *shape* of the *measurement* (i.e. *what* to measure), the volume of air can be the *space* of the *measurement* (i.e. *where* to measure) and the *time* represents *when* the temperature is measured. Each one of these three elements is defined as *property*.

Each *property* is involved in one or more *transformations*: a *transformation* is a mathematical relationship between a set of *properties*. For instance, the relationship between the temperature and the time in which it is measured is the *transformation* $T=f(t)$, where t is the time of the *measurement*, T is the temperature and f is the mathematical relationship that links the two *properties*. (Each *property* has to be detailed by a *range of values*, a *UOM* (unit of measure) and a *tolerance* of the *measurement*. For instance, the *shape* of the *measurement* can be measured in Celsius degrees (*UOM*) between 25°C and 50°C (observed *range of values*) with a *tolerance* of ± 0.1 (i.e. the error of the measurement system).

A set of mathematical relationships between the properties of a set of *measurements* is defined *experience*. An *experience* is a kind of report of experiment: the constant parameters (*properties* that are constant during all the observations) and the observed variables are all formalised as mathematical relationships between *measurements*, i.e. as *transformations*. As an example, let us consider an experiment to test the validity of the ideal gas law $PV=nRT$ (an instance of *transformation*). The instance of the *experience* has to capture the mathematical relationships between all the (S, T, S)s of the *measurements* (e.g. the pressure, the temperature, the volume of the gas considered) that describe the environmental conditions where the law holds. In other words, the *experience* instance describes a system behaviour and in which conditions this behaviour should be observed.

3.2. Extending the meta-model for the human-machine interface

The conceptual model described in the previous section was intended to formalise knowledge for an automatic or semi-automatic reuse. This implies the absence of human readable descriptions of the formalised instances. In this paper we extend this conceptual model to allow an easier user knowledge formalisation. The ambiguity of the instances is not expected to increase, i.e. each one of the contents should be disambiguated on the basis of the measurement system. In other words, we need to:

- Introduce new concepts to allow a non-expert user interaction and a multi-perspective descriptions of the basic concepts about the systems behaviours (e.g. products, manufacturing processes) described in (Giovannini et al., 2015).
- Introduce concepts to improve the accessibility of the knowledge base content at multiple levels of detail; especially, a non-expert user should be able to reach the desired concept by filtering the results not only on the basis of the numerical concepts, as in (Giovannini et al., 2015). In Fig. 1, the conceptual model extensions are

shown: the blue relationships are modified ones; the green artefacts are added ones.

3.3. The abstraction of the concepts of UOM and space

To improve the accessibility of the content, we studied different ways to group the basic concepts of *measurement* and so on. Since the *measurement* is a composition of *properties*, the research in the knowledge base should be based on:

- *properties* (S,T,S):
 - UOM;
 - UOM and tolerance;
 - UOM range of values;
 - UOM, tolerance and range of values.
- *experiences*.

The *time* (i.e. when the measurement is captured) has not been considered as basis for a content research. In fact, the time of the measurement is composed of two terms: the start and the duration. These ones are numbers in a scale that is unique for the experience. Therefore those values make no-sense if not considered in the context of an experience.

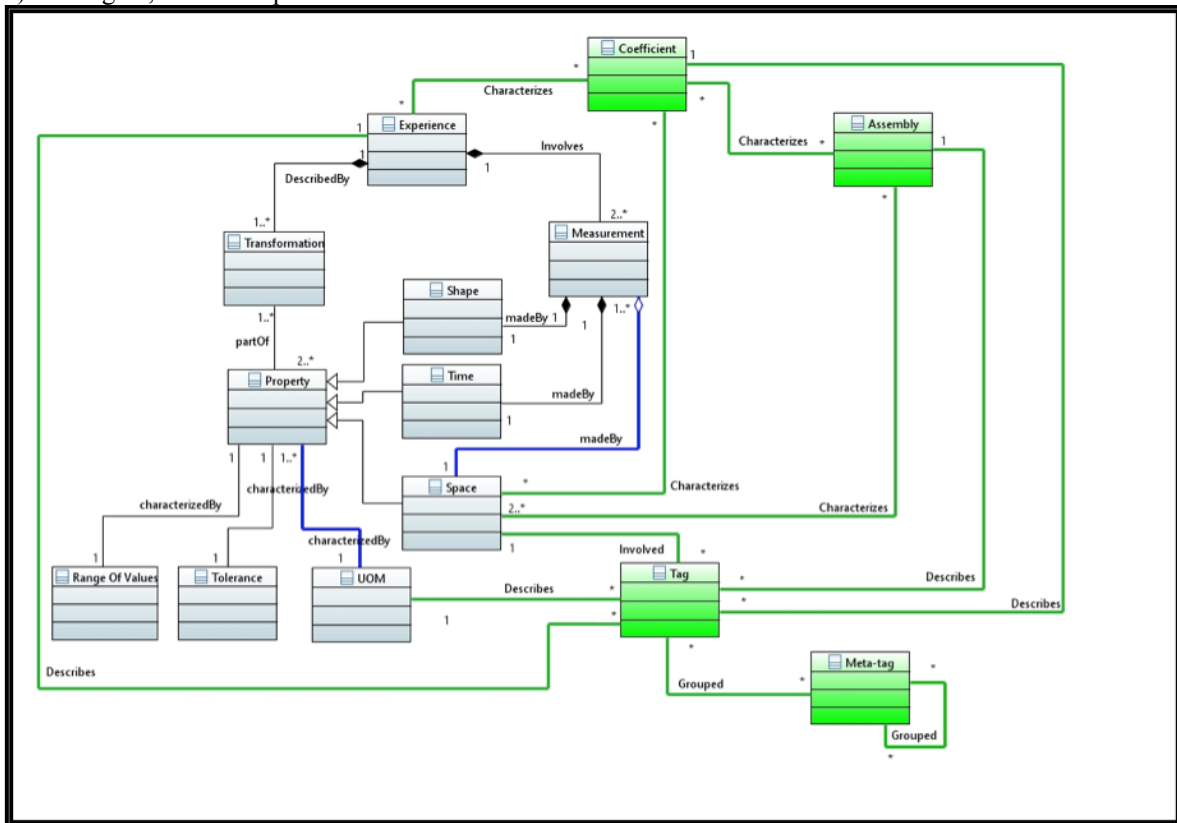


Fig. 1 – The adaptations to the metamodel in (Giovannini et al., 2015): the blue lines are the modified relationships; the green artefacts are additions.

All the other concepts in the previous list were experience-dependent in model in (Giovannini et al. 2015): *UOM*, *range of values* and *tolerance* existence depends on the *property*; the *property* existence depends on the *measurement*; the existence

of the latter depends on the *experience*. The first adaptation of the model in (Giovannini et al. 2015) dealt with the “abstraction” of concepts originally part of a UML composition or a 1-to-1 relationship: the UOM and the *space*

has been identified as important *objects* that can ease a content research. Let us consider two system behaviours: the first one describing the light diffusion in a room; the second one describing the heat exchange in a room. The concept of “window” is in both cases involved in the systems. Without the abstraction of the concept of *space* there is no chance of finding the two experiences by querying the word “window”.

Therefore, the relationships that linked UOM with *property* (1-to-1) and *space* with *measurement* (composition) to the other classes have been changed (blue relationships in Fig. 1) into 1-to-many relationships.

Other concepts like *time*, *range of values* and *tolerance* have not been abstracted because they are too related to *experience* and *UOM*.

3.4. The definition of two concepts: coefficient and assembly

As discussed above, the system behaviour is described by means of mathematical relationships between properties. The abstraction of the concepts of *space* and UOM has made possible a research for the measurements. Instead, it is still not possible to discriminate the experiences by the described behaviour. To do so, we defined the concept of *coefficient*.

In the mathematical models characterising an experience, there are parameters related to the *measurements* (i.e. direct measurements) and other parameters (e.g. heat exchange coefficient) that are related to indirect measurement and therefore not represented in (Giovannini et al., 2015). The *coefficient* concepts are here used to describe how the measurements relate in an experience. Therefore the coefficients are intended to express the type of behaviour we want to characterise in the knowledge base.

Since coefficients describe relationships between measurements, they are linked with the *experience* class in Fig. 1. The coefficient class is also related to the *space* concepts because the coefficient can relate measurements with the same space. However, when a coefficient relates measurements with different spaces, a new concept is required because, in the original model, there were no space aggregations

To associate a coefficient describing the interaction of two measurements related with two different spaces, we defined the concept of *assembly*. In Fig. 1, the *assembly* class is related with the *space* and the *coefficient* classes.

3.5. The definition of tags and meta-tags

In the previous sections, we introduced concepts to group elements and to increase the expressiveness and reachability of concepts like *UOM* and *space*. However, the research of the content is still based on numbers and units of measure. Originally, the conceptual model was intended to formalise a machine-readable knowledge. To make the interface more user-friendly, descriptions of the models and spaces – and generally of the numerical values – should be provided. These descriptions must not introduce ambiguity in the model.

To cope with this point, we should provide a 1-to-N relationship between the contents and the related description. This cardinality allows us to express the points of view of more users without generating ambiguity. In fact, a description is related only to one content, so the disambiguation is transposed to the metamodel in (Giovannini et al., 2015): i.e. a description-based research results in a unique artefact of the metamodel in (Giovannini et al., 2015). In Fig. 1, the descriptions of the contents are defined *tags*. The *tag* concept is a one-word description associated with all the researchable concepts of the model, i.e. *UOM*, *space*, *coefficient*, *assembly* and *experience*.

When a user performs a tag-based research, the results are directly connected with the original concepts that are intended to disambiguate the knowledge on the basis of the measurement system. Consequently, the *tag* introduction does not alter the ambiguity of the formalised models.

To speed up a research based on descriptions and to associate related descriptions, a concept to aggregate the *tags* is required: in Fig. 1 the *metatag* concept has been added. A *metatag* can be related to more *tags* or *metatags*. These relationships allow to build several levels of aggregations.

4. THE METAMODEL IMPLEMENTATION

The extended metamodel has been implemented with a MySQL database. The DB is accessed from the web. The aim was to allow the concurrent DB instantiation.

The *spaces* are mainly represented with CAD software. When CAD models are not available, schemas or images can be uploaded. The aim is to represent where the measurements are captured, i.e. where the sensors/actuators are installed during the experiment to be formalised. To make easier the introduction of related spaces, it is possible to upload a CAD assembly model. An interface has been developed to read the assembly model and build the related *assembly* and *space* instances in the DB.

The *transformation* that represent the mathematical relationships between the measurements’ *properties* are formalised in scripts or MINLP models to be launched with a solver. In these files, there is the list of *properties* that are displayed in the graphical representation of the DB instances (Fig. 2). The user should link each *property* to the related *space* and so to the *space*-related *measurement*.

The web interface allows the users to add *tags* on the nodes in the graph (Fig. 2) and *metatags* on the *tags*.

5. CASE STUDY: 4 INTERFACES USING THE META-MODEL

In this section, we describe 4 applications that are based on the implemented core-metamodel. Each application queries the model to fetch the required data to pursue the assigned aim. The DB structure and instantiation mechanisms remain the same. The way the applications queries the DB determines the usage of the same data. An update on the data in the DB has effects on all the linked application. The four examples here described are only few applications that can use the enterprise knowledge. Several other applications can be designed and developed to use the same core-metamodel.

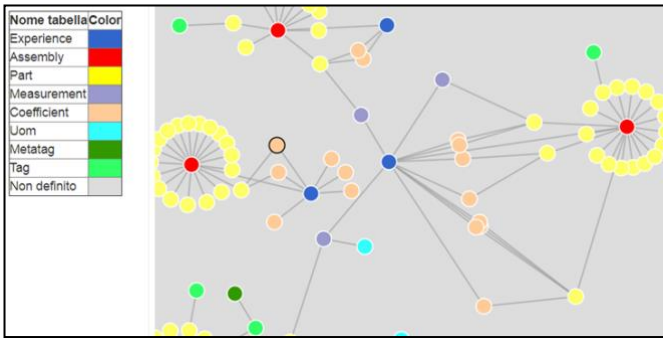


Fig. 2 – A screenshot of the graphical interface: each colour represents an instance of a different class.

5.1. Smart manufacturing traceability app

The aim of this application is to monitor the coherence of the materials traceability information in a shop floor. To maintain this information the application needs updated data about the manufacturing processes and the process parameters related to the ordered products. This application use the knowledge about the products described in the DB. When a product order is introduced, the name of the product is queried in the DB. The product (i.e. the *space* in an experience) is linked to the manufacturing processes (i.e. other experiences which have CAD files tagged as outputs that corresponds to the ordered product) and the related process parameters that the traceability app needs to trace. When the order of a new product is performed, the app synchronises the internal information with the DB. To use this application, it is not required that a user is an expert of traceability best practices, because by means of the knowledge in the interface supports the users.

5.2. CPS for the optimisation of M2M interaction

The aim of this app is to optimise the scheduling in real-time to exploit energy saving opportunities. We developed a prototype that implements the hybrid architecture in (Dassisti et al., 2017) for the M2M interaction (Fig. 3). The proposed hardware interacts with PLCs that simulates the industrial controllers. At each order entry, a central unit synchronize the manufacturing process knowledge with the DB to update the interaction control rules applied by the machines. The *transformations* in the DB are here used to decide the best operating parameters of each machine to save energy. In the

case of the prototype three scripts in the DB are downloaded at the order entry and used by the proposed hardware (the three electronic devices in the lower part of Fig. 3) to communicate the best motor speed ramp. The users don't need to know the alternatives of the manufacturing processes. The system will choose the best solution for them.

5.3. Augmented reality assembly support app

The aim of this app is to support the assembly stage of small assemblies in a scenario of high product variety. The app generates automatically an approximated assembly sequence by improving the algorithms in (Dini and Santochi, 1992). The generated sequences are sent to the cloud and read by an AR holographic device that reproduces the sequence on demand. At each assembly request of a new product, the app synchronises with the DB to download the CAD data of the product. On the basis of an API to interact with the CAD model in the DB, the constraints between the parts in the assembly are retrieved and sent to the assembly sequence generator.

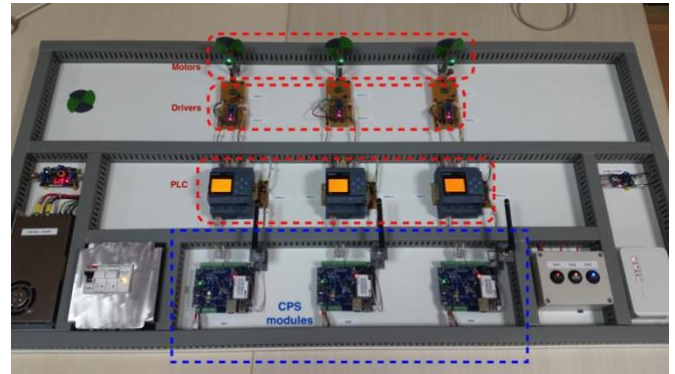


Fig. 3 - picture of the CPS prototype: three brushed motors are controlled by the PLCs; each PLC is connected with the proposed hardware to make them communicate; details in (Dassisti et al., 2017).

5.4. App to support the real-time data interpretation

The aim of this app is to support the analysis of real-time data from monitored systems. The app allows a user to subscribe notifications: the user describes its interests on the basis of the *tags* and *metatags*. A monitored system expert describes the real-time data by using the *measurements* and the *transformations* in the DB. The app uses the *transformations* to analyse the data and provide predictions to be communicated to the users on the basis of the *tags* and *metatags* they used to describe their interests.

6. DISCUSSION AND CONCLUSIONS

In Section 2 we have identified two main requirements that must be satisfied to promote the I4.0SMEs solutions: *knowledge-based* and *extensible*.

As shown in the applications presented in Section 5, it is not required that the users have a deep knowledge about the application domain because a system that use the knowledge

formalized with the proposed metamodel is able to properly support the users.

About the last requirement, all cases described in Section 5 use the same metamodel to formalize different knowledge without change anything about the formalization rules. So, the same DB can structure knowledge for different domains that can be used for different applications.

In this paper, we presented a metamodel based on the concept of measurement (related to sensors/actuators). The proposed metamodel represents the extension of the another ones, previously presented in (Giovannini et al., 2015). We implemented the new metamodel to favour the adoption of the I4.0 solution in the SMEs that are characterized to the lack of structured processes, expertise and resources, that make the I4.0 implementation even harder. The metamodel has been implemented in a DB and a web interface and tested on four prototype-apps. Each app interacted with the DB to query information to perform the required functionalities. The knowledge formalised in the DB and the querying process in the apps allow an easier implementation of apps for real-time data analysis, M2M interaction optimisation, smart traceability and AR supported assembly process.

The limits of the proposal are still related to the knowledge mapping in the DB. Ideally, a CAD files comparison can increase the integration of knowledge modules and their reachability. Moreover, other apps should be tested to perform a knowledge flow toward the DB: i.e. machine learning applications. This flow would allow to autonomously update the knowledge base of all the apps linked to the DB.

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