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Knowledge capturing and reuse to support manufacturing of customised products: A case study from the mould making industry

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Abstract

Manufacturing activities are characterised by high repetitiveness and the generation of vast amounts of data, which however remain underutilised and in most cases completely unexploited. However, new design and planning projects share numerous commonalities in their processes, materials and resources with past cases. Leveraging information, which is created and distributed among workers, departments and partners of a company through its transformation into knowledge can enable the coordination between the phases of product design and manufacturing, especially in the context of engineered-to-order products. Knowledge intensive industrial sectors that manufacture one-of-a-kind products or several product variants, such as the mould-making, can benefit from the reutilisation of past knowledge. This research work aims to the systematic capturing, storage and retrieval of knowledge about engineering projects and enable its reuse in the design and planning phases. The case-based data model, the components of the knowledge reuse engine and a set of knowledge enriched apps are presented. The application of the framework is demonstrated through a real-life case study with data coming from the mould making industry.

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1. Introduction

Manufacturing activities in the era of mass production were characterised by the repetition of the exact same tasks for the procurement of identical parts and products. In todays' era of mass customisation and personalisation, on the other hand, product variety has increased immensely reaching occasionally lot sizes of one [22]. The repetitiveness of similar design and planning tasks, however is still characterising the majority of the daily process of contemporary industries. In addition, vast amounts of data are generated on a daily basis, which however remain underutilised and in most cases completely unexploited.

The reuse of stored data through their leverage into knowledge entails significant potential for manufacturing [16]. However, knowledge capturing and extraction is far from trivial [14]. A difficulty lies in the fact that knowledge can be found scattered across different technical areas of the company [1]. In addition, capturing subjective and therefore tacit knowledge regarding product and production activities is a complex procedure. Finally, verbal communication among workers constitutes an impediment for the documentation of experience and reuse of engineering knowledge.

Nevertheless, the importance of knowledge for manufacturing is evident, considering that, for instance, over 60% of design tasks are common between past and new engineering projects.

The exploitation of knowledge in data intensive industries has been identified as an enabler for better organisation of the company, increased transparency, identification of competitive advantages and higher profits [4]. In the context of SMEs, the process of capturing knowledge is feasible due to the restricted magnitude of operations and manageable influx of information.

The presented research work aims at capturing and reusing knowledge during the initial requirements collection up to the planning phase to support SMEs that operate under an engineer-to-order business model.

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2. State of the Art

The importance of knowledge reuse for the early design phase of product and system is evident, as rough estimates indicate that around 20% of a product designer's time is spent on searching and absorbing information, a figure that gets even higher for technical specialists [4]. A recent study investigated the role and usage of expert knowledge in the domain of injection mould manufacturing and presented a method for capturing knowledge based on verbal discussion with engineers and technical documents' inspection. The results from a case study depicted a reduction in lead times were observed of up to 55% compared to the conventional process [1]. Baxter et al., reported a method for reusing design knowledge, which considered the interaction between design process models and product data models through a set of parameters in order to meet particular needs of engineering design during the lifecycle of the design phase [3]. The study however, considered only a very narrow spectrum of a product family, thus its scope was limited. An attempt for potentially more efficient reuse of knowledge is proposed in [6] through the separation between information and knowledge. Specifically, product and manufacturing process knowledge are distinguished and classified into different layers according to the selected manufacturing strategy. A framework for the definition, storage and extraction of past knowledge regarding production line layouts is demonstrated in [2]. Through a case study taken from the steel construction and forging industry, the paper aims to support the early design phase of the system by employing a semantics approach for the knowledge representation and storage while utilising similarity measurement and inference techniques for knowledge extraction. The utilisation of knowledge to facilitate platform-based product realisation is presented in [9]. A knowledge repository is reported that is used for storing previous assembly line designs and retrieves similar information for new design projects upon request. The authors in [5], propose new semantic-based Virtual Reality techniques for use in prototype designing and review and applied the method in a real-life case study coming from the aerospace industry. Both 3D geometries and interaction metaphors could be reused in new cabin design applications and simulation scenarios.

Moreover, knowledge reuse has been attempted during other engineering domains, such as process planning. lifecycle management and project management. Process plan generation for multiple product variants based on hierarchical, historical and case-based knowledge is presented in [7]. Consequently the task of process plan generation reusing previous knowledge is enabled. The Process Specification Language (PSL) standard proposes a generic ontology for the representation of manufacturing processes, enabling the exchange of process information and knowledge. PSL defines a neutral language for process specification to integrate multiple process-related applications throughout the manufacturing life cycle [13]. The semantic Virtual Factory Data Model (VFDM), developed under the European project Virtual Factory Framework (VFF), provided a hierarchical holistic structure of sub-ontologies related to Factory, Building, System, Resource, Process, Product, Strategy, Performance and Management, enabled by a management module. The aim of the framework is to allow the definition of a virtualised factory along all the phases of its lifecycle [15].

Last but not least, commercial tools such as SAP AG's Knowledge Warehouse [10], Teamcenter from Siemens [11] and Dassault's CATIA V5 Knowledgeware [12] basically facilitate the development and distribution of product and process documentation instead of true knowledge management features.

2.1. Gaps of knowledge-based approaches in manufacturing

The research work on the topic of knowledge management in a manufacturing context is abundant. A number of ontological approaches have been proposed. However, ontologies have practical limitations. In case an ontology is abstract, its applicability and problem solving potential may be diminished. On the other hand, in the case of very specific ontologies, reasoning and knowledge inference capacities are limited. For effective knowledge reuse, the underlying data model should have an appropriate level of details in respect to its use, a characteristic that is missing from many reported implementations and is attempted in the proposed approach. In addition, the majority of the scientific publications in the field are concerned only with design knowledge about product, system and service [8], while the proposed approach focus also in the planning of the production phase. Finally, exploiting the potential of knowledge reuse through intelligent software apps is scarce in the industrial context.

In the present research work, a knowledge-based framework is defined, hereby referred to as Knowledge framework for Advanced Manufacturing (KAM), which is composed of a domain specific case-base data model, a case-based inference engine and a similarity mechanism. KAM allows for knowledge reuse in the context of product and process domains for engineered-to-order products. A set of intelligent engineering apps are deployed on mobile devices and exploit the information generated by the daily activities of the company by leveraging it into reusable knowledge.

3. Knowledge framework for Advanced Manufacturing

The interconnections between the different components of the framework are depicted in Fig. 1 using the IDEF0 notation.

The core element of KAM is the knowledge repository, whose primary purpose is the storage of the case-based data model and the storage of knowledge in terms of rules and cases. The knowledge repository imports, uses and updates the data model schema, which described the entities and their inter-connections. KAM has been developed as a web-based application following a 3-tiered (presentation, business and data tier) client-server architecture under the Model-View-Controller design pattern [21].

The Apache Tomcat webserver hosts the application. Moreover, a set of web apps have been developed and are discussed in section 3.4 below.

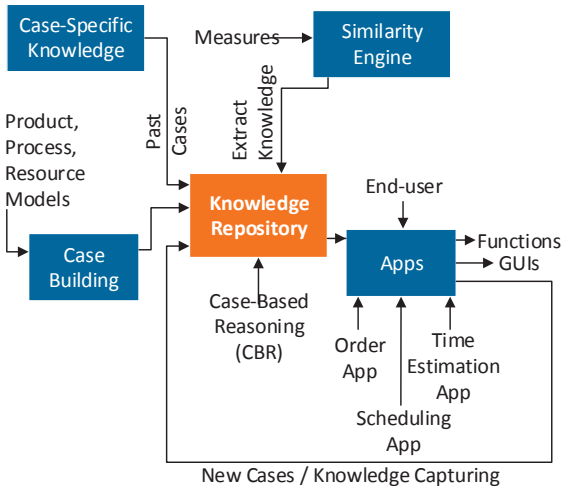

Fig. 1. IDEF0 Architecture of the Knowledge framework for Advanced Manufacturing

The apps are of varied complexity and have different computational requirements. Thus, they are deployed to different devices that can handle the computational complexity as depicted in the diagram of Fig. 2.

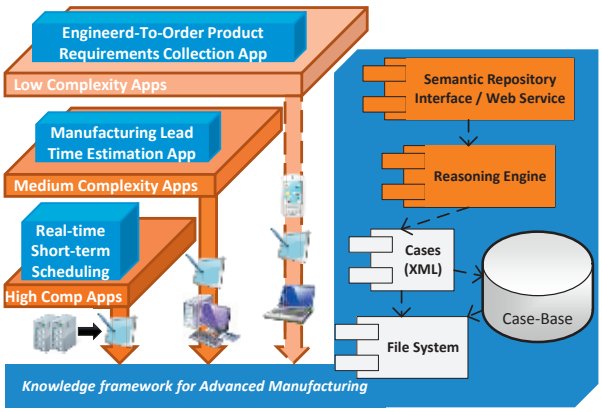

Fig. 2. The KAM Framework

3.1. The Manufacturing Case-Base

The backbone of the KAM framework is the manufacturing case-base, which explicitly defines information about product, process and resource and clusters this information into cases. The case-base is developed into an easily importable XML schema that accommodates all structural relationships and physical properties needed to explicitly describe essential entities. The core classes and their interconnections are depicted in the class diagram of Fig. 3. The Suppliers class defines information about the name, contact details, location, as well as other manufacturing specific details, such as number and capabilities of the machine shops and capacity. Supplier instantiations may include suppliers of parts or of entire components of the product. The entities Parts and Components include name, part / component type (auxiliary, guide, etc.) and dimensional data information and belong to the Mould, which is the core entity of the model. The Mould datatype includes information regarding the name of the mould, the number of cavities, the cooling structure and any specific surface quality attributes. Moreover, information related to the wall thickness of the injected product, the earpins, existence or not of tamper evident, polishing, way and side of injection and related Bill of Materials ID are included. The Bill of Material ID is a reference to an external Product Data Management software suite. The communication with this external legacy system is achieved using web services. Moulds are used by the datatype ResourcesCustomer. This class models the machine available on the customer side that will use the mould for plastic injection. The Processes datatype describes the type of process (roughing, finishing, inspection, transportation, measurement, hardening, grinding etc.) and the processing time. Moreover, the Resource models all elements found in a machine shop. A Resource generalises the types Human, Machine and Buffer and contains information about the type, capabilities, operating cost, as well as tools, jigs and fixtures. In addition, the facility is modelled in a hierarchical structure that includes the plant that contains job-shops, which are clustered into work-centres that include resources.

3.2. Case-based reasoning engine and Similarity mechanism

The inference engine of KAM includes two mechanisms for knowledge extraction, namely the Case-Based Reasoning (CBR) and the similarity measurement engines. The CBR procedure is followed due to its suitability for complex ill-defined concepts, where knowledge is not structured properly and case generalisation is required [17]. CBR consists of the following five steps applied to the cases: 1) representation and storage, 2) retrieval, 3) reuse, 4) adapt and 5) retain. The similarity measurement engine utilises distance measurement algorithms for the identification of similarities in previously executed scenarios. For each newly requested case, i.e. new product order, the engine compares its features with stored cases in order to reuse acquired knowledge. The pairwise comparison is based on distance measurement between features that include: the number of cavities, type of hardening, side of injection, mould size, core cap, ejector rings, temper evident, surface's quality and number of basic components. The distance is measured by employing a slight modification of the Minkowski distance of the second order [23]. The measure incorporates a simple normalisation of the values within the range [0,1]. As the measure expresses the distance between the past and the new case, its value is subtracted from the unit in order to derive the similarity between the cases. The similarity is expressed though eq. (1).

$$Sim(T,S_j)=\sum_{c=1}^{C}\left(1-\sqrt{\left(T-\frac{S_j}{T}\right)^2}\right) \quad (1)$$

where, T is the new (Target) case, S are the past (Source) cases, j is one of the past cases, c is the compared attribute between past and new case and w is the weighting factor for the cth attribute.

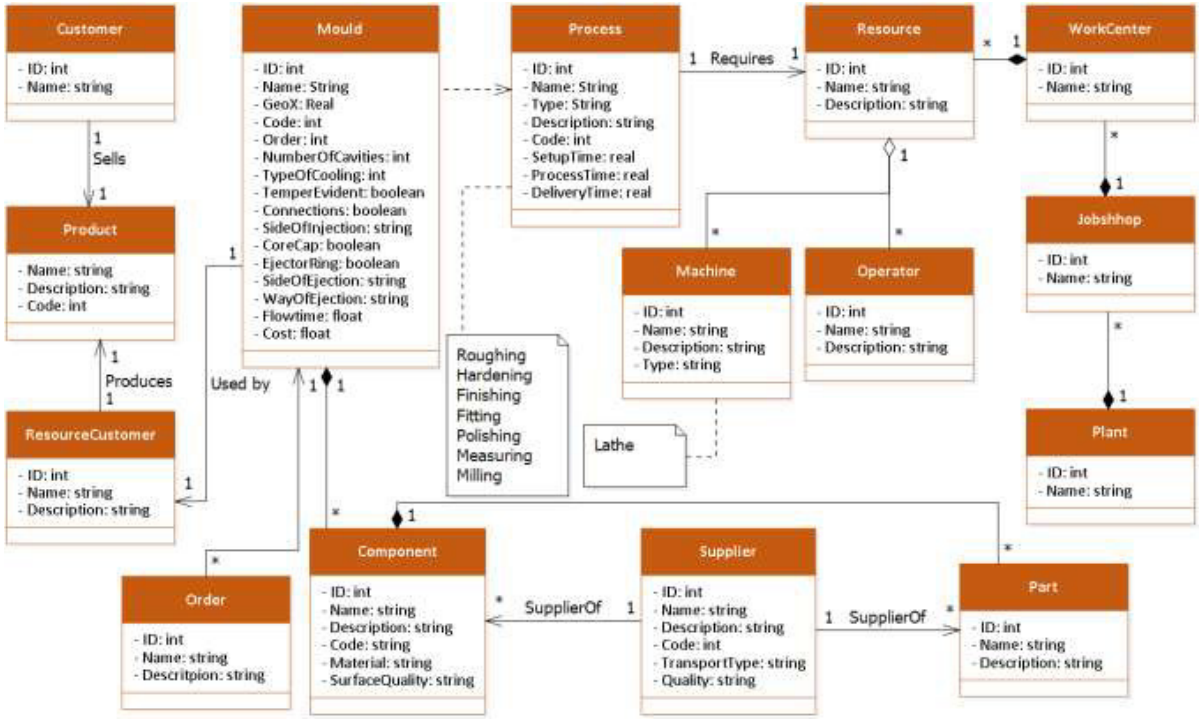

Fig. 3. Data model depicting the structure and interconnection between the core classes of the case base

3.3. Knowledge enriched mobile applications

A set of standalone apps integrated on the back-end data level are interfaced to the KAM and exploit its knowledge reuse capabilities. The apps focus on supporting specific design and planning phases for the realisation of engineered-to-order (ETO) products. An app for capturing the customer preferences has been designed in order to directly translate newly placed product orders into cases that are stored in the case-base, continuously enriching the case-base by providing additional training data. The second app is responsible for providing an estimation of the required manufacturing lead time in order to produce the new ETO product. The similarity mechanism compares the new case with the stored cases as described in Section 3.3 and returns an estimation of the lead time. The result is available in near-real time and accompanies the quotation provided to the customer. Finally, the short-term scheduling app is responsible for generating the production Gantt chart by assigning resources to manufacturing tasks with the respective processing and setup times [24]. The CBR methodology retrieves previously executed schedules, identifies the most similar and adapts it according to the current state of the machine shop. The production planner reviews the schedule and dispatches it to engineers and machine operators. All apps are currently under development and will be available through a cockpit web app that runs on PC-based systems, Android and iOS devices.

3.4. Tools for the development of the KAM

The tools used in the development of the knowledge reuse framework are described hereafter. The J2EE programming framework is used of the implementation of the web-based framework. The open source FreeCBR has been adapted for the execution of the CBR engine [20]. Apache Tomcat v7.0.47 hosts the web application and handles data manipulation. Tomcat also contains the business logic of the framework. HTML is utilised for browser rendering of the GUIs of the framework and JavaScript enables user-system interactions. Data transfer from and to the framework (e.g. legacy systems) is also performed through XML schemes.

4. Industrial case study from the mould-making industry

The case study in the present work is taken from the mould making industry. As a region, the European Union likely ranks as the largest producer and consumer of industrial tools, dies and moulds (TDM) in the world with a relatively small number of tooling producers in each EU member country. The industry in Europe represents an average annual turnover of 13 billion USD and comprises more than 7,000 companies, 95% of them being SMEs, representing a high added value workforce (more than 100,000 workers directly in the sector) with a remarkable know-how in design and manufacturing processes [18].

The entry point of the current state of the case study is any incoming injection mould order. The process is carried out through the filling of a requirements form, which comes in hardcopies and is filled in with the details of the costumer (name, company, telephone number, email etc.) and with the product's specifications (raw material, colour, packaging, number of cavities, surface quality etc.). When the collection of the requirements is finished, the order is classified as a new

project (case). The order, in its final form, is dispatched to the financial, engineering and administrative department of the company. The offer is prepared in terms of delivery time and cost based on the experience of the staff and administration. During the mould designing phase, the detailed 3D CAD drawings of the mould parts are created. Afterwards, during the manufacturing phase, the process plans for its production are generated manually. The required processes, their sequence, the selection of machines and cutting tools are documented by the engineering department. The process planning method is carried out using the variant approach [19]. The actual manufacturing procedure follows, which comprises of roughing, grinding, milling, drilling, finishing, inspection and measurement. Following on that, the mould is tested in real-life production settings for the identification of possible discrepancies and any other deviations from the initial specifications. Possible refinements are outlined and are carried out in the next phase. The identified corrective procedures are implemented in this phase. Possible activities may include, surface of cavities and contact surfaces, checking for any missing features (pockets, fixtures, etc.) as well as the final quality inspection. Additional testing of the real production settings is done in order to ensure the quality of the produced mould. Finally, the finished mould is delivered to, or in particular cases picked-up by the customer.

4.1. Issues faced in the current approach

The above process entails numerous issues. During order data collection, customers are hesitant or incapable to provide fully detailed requirements. Afterwards, the company has to prepare the offer to the customer, including a preliminary estimation of the delivery time. The estimation is based solely on the experience of the engineers, since the estimation includes rules of thumb and not a systematic approach. This leads to an estimation accuracy close to 15-20% compared to the actual delivery time. During the mould manufacturing phase, no short term scheduling is performed, and therefore the performance of the facility in terms of cost and time is far from optimal. A number of shortcomings are also spotted in terms of data information and knowledge management. Lack of documentation is observed, since the expert operators must have an assistant that is constantly keeping notes on-the-spot for specific production problems. Detailed documentation cannot occur during normal working time, and must happen after shift, an action hampered by the natural fatigue of the workers. Finally, expert operators are hesitant to document the problems, and share incomplete knowledge.

In light of the identified problems currently faced by the company, the proposed KAM solution is focused in two directions: the framework aims to facilitate communication and collaboration with customers and can be utilised in the data collection phase as well as during planning of production focusing on increased utilisation of resources and shortening of delivery times. The proposed solutions are envisioned to support indistinctively the needs of the company for the development of either a new product or a product variant (Fig. 4). It should be noted here that a beta version has already been implemented for the Requirements Collection and for the Delivery Time Estimation apps.

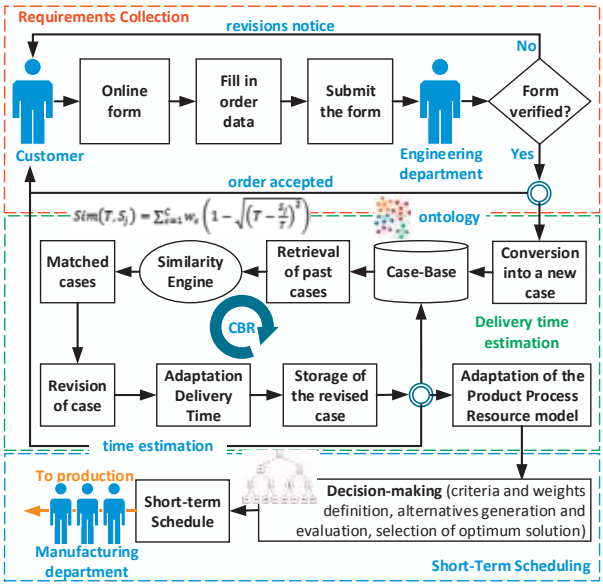

Fig. 4. Workflow modelling of the case study

The theoretical background of the short-term scheduling app has been developed and currently the initial software design phase is ongoing. A more detailed view of the scheduling app is depicted in the diagram of Fig. 5. The engine of the scheduling app and the underlying decision theory are discussed in details in [21]. The previously stored executed schedules for the matched mould case are retrieved and are properly adapted to the current shop-floor conditions (resource availability, capacity, etc.). The modified scheduling case is stored in the repository as a past case.

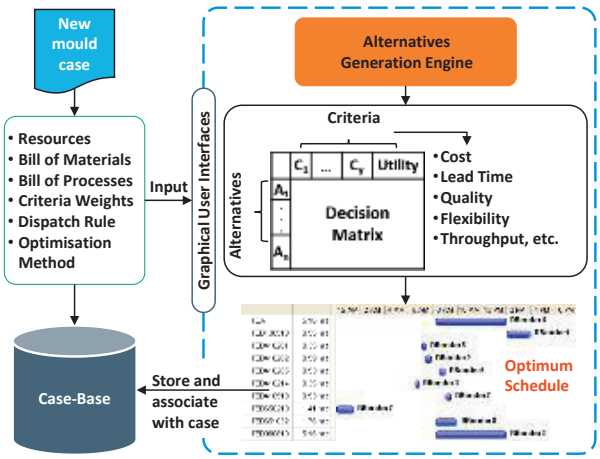

Fig. 5. Architecture of the short-term scheduling app

The KAM framework allows major improvements in terms of requirements collection. Customers are provided with a predefined template that enables faster communication and reduced number of iterations and human mistakes the

customer and the sales department. The requirements collection app will be accessible from standard browser technology and will be deployed on Android and iOS operating systems. This App will be based on the existing knowledge and will comprise of a checklist that will be developed in collaboration with design engineers; it will consist of the necessary information for mould design and can be adapted according to the specifications of each mould. The delivery time estimation app provides the customer and the sales department with a semi-empirical estimate of the delivery time. Moreover, since long-term scheduling is not feasible, given the complexity of the tasks and the high number of unpredictable rush orders the system performs, a delivery time estimation that extracts data from the present workload of the factory, the specifications of the new order that enters the system and the experience from past cases. The short-term scheduling app will then optimise the short-term schedules. The app generates and evaluates alternatives schedules, calculates performances indicators for each production line and optimises the schedule based on time cost and other performances indicators. The production manager will be informed by an accurate and comprehensible visualisation of the scheduling through Gantt charts, workload analysis and production line resources structure.

5. Discussion and Conclusions

Among the main reasons for the limited application of knowledge reuse systems in manufacturing is the absence of sufficient domain-specific ontologies or case-bases in terms of level of details, as well as a scarcity of applications in the framework of digital manufacturing that are knowledge-enriched or integrated through knowledge to intuitively support design and planning activities of modern SMEs. Finally, it became apparent that the vast amount of generated and stored data are not utilised in similar new engineering projects, thus potential cost and time savings are not exploited.

Towards that end, the proposed Knowledge framework for Advanced Manufacturing (KAM) provides a domain case-base with knowledge reuse capabilities to support engineered-to-order product realisation and enhance software applications with knowledge reuse capabilities. The envisioned apps communicate and are be integrated with legacy systems through knowledge instead of connecting technologies.

Future work will focus on extending the already modelled domain knowledge and increase the capabilities of the KAM. An extension of the datatypes and their attributes in the underlying case-base will be performed. Further to that, the implementation of the knowledge enriched apps will be finalised and the KAM framework will be deployed and tested in a two real industrial pilot cases.

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