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# Enterprise information systems interoperability for asset lifecycle management to enhance circular manufacturing

**Adalberto Polenghi*, Federica Acerbi*, Irene Roda*, Marco Macchi*, and Marco Taisch***

**Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy {adalberto.polenghi, federica.acerbi, irene.roda, marco.macchi, marco.taisch}@polimi.it*

**Abstract:** The present work considers information and data as a cornerstone for an effective Circular Manufacturing (CM). Focusing on complex industrial assets it also postulates the relevance to develop CM strategies having both the perspective of the Original Equipment Manufacturer, or asset provider, and the asset user. In this scope, a particular emphasis is given on enterprise information systems interoperability as enabler: for CM strategies to be effective, data are required to be exchanged between various enterprise information systems (EIS) hold by the two parties. Therefore, the mapping of data required for each CM strategy along the product/asset lifecycle is performed, and an overview of the EIS interoperability for CM enhancement is discussed, leveraging on ontologies concept.



*Keywords:* Circular economy, circular manufacturing, asset lifecycle management, interoperability, enterprise information systems, ontology, manufacturing, sustainability.

## 1. INTRODUCTION

Nowadays, Circular Economy (CE) is driving companies in adopting strategies that will cope with sustainability goals. Indeed, CE is defined as an industrial economy designed with the intention to regenerate resources (The Ellen MacArthur Foundation, 2015). It has been widely applied in manufacturing, thus declined as Circular Manufacturing (CM), to enhance sustainable performances through different strategies, like circular design, cleaner production, recycling, etc. (Acerbi and Taisch, 2020). In this context, the industrial Asset Lifecycle Management (ALM) covers a prominent role in undertaking an effective circular transition (Stahel, 2007).

The ALM involves several activities to be performed, from the design, realisation, and commissioning of the asset in BoL (Beginning of Life), through operation and maintenance in MoL (Middle of Life), to decommissioning (End of Life) (Institute of Asset Management, 2015). Each activity implies different decisions to be taken and different stakeholders' interests to be properly balanced (Roda and Macchi, 2018). Thus, the asset is not seen from a unique standpoint, but multiple visions exist, each depending on the considered party (Schmidt et al., 2017). Amongst relevant stakeholders, the Original Equipment Manufacturer (OEM), or asset provider, and asset user represents two of the most impactful parties over the asset lifecycle (Roda and Garetti, 2014).

Actually, a complex industrial asset (e.g., an industrial centrifugal pump) is managed as a product by the asset provider, and it becomes an asset embedded within the manufacturing plant / industrial facility when the perspective is moved to the asset user (Acerbi et al., 2020). This typically involves a change of ownership. Thus, the ALM becomes itself a complex system (Fig. 1) where the asset provider and user need to collaborate to assure optimal CM performance, based on shared data and information (Rossi et al., 2020).

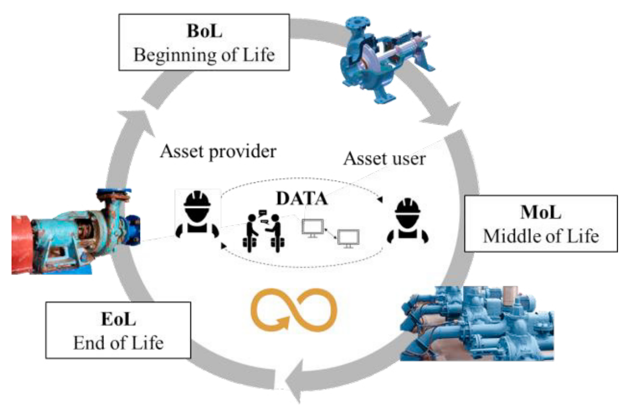


Fig. 1. Research scope: asset provider (OEM) and asset user exchanging data along the asset lifecycle to enhance CM.

In this scope, the product-oriented approach of the asset provider and the asset-oriented approach of the asset user need to be integrated leveraging on data exploitation for enhanced CM strategies adoption (Matsokis and Kiritsis, 2010). This implicitly requires to streamline the information flows between asset provider and asset user, adapting the traditional Product Lifecycle Management (PLM) for CM paradigm so far engaged (de Oliveira and Soares, 2017) to the ALM one. This leads to focus on information and data as a cornerstone for CM enhancement (Acerbi et al., 2021), as the main interest of this work, with a particular emphasis on enterprise information systems (EIS) interoperability as enabler. Thus, the research methodology consists of: i) mapping the data families and CM strategies, considering those exploitable for ALM, based on the PLM theory (section 2); ii) an analysis of EIS ecosystems for ALM on asset provider and user sides, to pave the way for ontology-based interoperability for CM enhancement (section 3). Section 4 summarises the findings, orienting towards future research.


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## 2. DATA REQUIREMENTS FOR CM STRATEGIES

The different CM strategies studied and implemented so far in the industrial and academic world, are here presented, followed by an analysis on required data families.

### *2.1 Overview on CM strategies for ALM*

Several strategies are adopted in the context of ALM for CM enhancement, even though they represent a smaller set if compared to those exploited in PLM (Acerbi et al., 2020). Fig. 2 proposes a summary of these strategies, framed according to the asset lifecycle, leveraging on PLM literature.

| | | | |
|---|---|---|---|
| **ALM** | **BoL**<br>Design Manufacturing Distribution/ Commissioning | **MoL**<br>Use & Support | **EoL**<br>Retire |
| **CM strategies** | **Circular design**<br>**Cleaner production**<br>**Resource efficiency** | **Servitization**<br>**Resource efficiency** | **Reuse**<br>**Remanufacturing**<br>**Disassembly**<br>**Recycling**<br>**Waste management** |

Fig. 2. Mapping CM strategies along ALM.

The most critical stage of the asset lifecycle for CM is the BoL since the decisions taken affect the sustainability performance (BS EN 8001, 2017). Circular design enables to figure out what characteristics the product must have to meet the CE values in the next lifecycle stages (Bocken et al., 2016). Thus, design for X approaches are adopted to limit detrimental consequences at product EoL (Marconi et al., 2017). Moreover, in BoL, the product manufacturing requires to be aligned with CE values, so cleaner production (Sousa-Zomer et al., 2018) and resource efficiency strategies (Choi et al., 2019) are adopted to limit material and energy consumption, and to reduce emissions.

In the MoL stage, when the asset is sold to the customer, the servitization strategy can be adopted (Guo et al., 2014). In the scope of this work, servitization is confined to the lifecycle extension through properly maintenance and repair services, also to establish a proper resource efficiency strategy (Holgado et al., 2020).

Finally, CM benefits can be visible in EoL where the residual value of the asset (or its components) can be regenerated. Indeed, the asset can be reused as it is (Liu et al., 2018), it can be remanufactured to its original quality (Sitcharangsie et al., 2019) or, last, the asset or its components can be recycled (Zhong and Pearce, 2018). If these strategies are not applicable, a proper waste management strategy should be put in place, in accordance to international and national regulations to avoid environmental and social impacts (Djuric Ilic et al., 2018). Transversal to these strategies, disassembly offers support to all of them.

For these CM strategies to be properly exploited, data should be integrated to positively impact on the asset lifecycle (de Oliveira and Soares, 2017). Thus, subsection 2.2 preliminarily maps which data competes to which strategy.

### *2.2 Data requirements for CM strategies exploitation*

Along the product/asset lifecycle stages a myriad of data is generated or used. However, discriminating which data is needed for a particular CM strategy to be properly exploited is fundamental to not fall in an uncontrolled ingestion of data (Mboli et al., 2020). Therefore, Table 1 summarises the families of data in the product/asset lifecycle, whilst proposing a preliminary mapping, based on selected literature, with respect to the CM strategy.

At the BoL stage, the product design follows the technical requirements, and, under CM, this implies to gather data enabling the regenerative paths of the product, thus addressing the circular design strategy. Information about product composition and construction, like technical drawings and user manuals, are generated in BoL, for circular design strategy, but especially usable at MoL, ensuring the asset appropriate utilisation. Also, assembly and disassembly instructions are generated at BoL but especially usable for the servitization strategy implemented at MoL enabling proper asset maintenance and facilitating the adoption of several CM strategies at asset EoL, like remanufacturing and recycling. In BoL, material composition needs to be tracked to appropriately implement recycling or waste management strategies, enabling the restoration of the resources embedded in the product or to manage the waste limiting the generation of toxic substances. Under CM lenses, at asset BoL data regarding product realisation and commissioning are required too. The former necessitates data about energy, material, and water usage to facilitate the implementation of cleaner production and resource efficiency strategies. The commissioning needs to be planned considering the product characteristics (e.g., transportation modes depend on product dimensions and user localization).

Moving to MoL stage, the data generated at asset MoL enable the asset provider to offer a tailored maintenance service by adequately implementing the servitization strategy (Jasiulewicz-Kaczmarek, 2018). Among those data, there are the adopted maintenance plan and the product conditions. The latter are influenced by the way the asset is operating, which could support resource efficiency strategy by the asset users. The MoL-related data are also useful to evaluate the applicable EoL CM strategy (Wong et al., 2012). Indeed, these data are necessary to define whether it is possible to reuse the asset within company boundaries or to sell it in a second hand market (Shaharudin et al., 2017), to evaluate eventual reuse by the asset user, to remanufacture or recycle it, or, eventually to manage the asset became waste.

At EoL, data regarding the product residual value determines the regenerative strategy to be adopted among reuse, remanufacturing, recycling, and waste management (Yang et al., 2019). The better the conditions are, the higher is the probability to reuse the asset or to easily recover it. Otherwise, it may require to be remanufactured, and if it is not possible, the components are detected to evaluate their recyclability, leaving waste management strategy as last option. These data need to be backed by data regarding energy, water, and material consumption for the regenerative processes. Last, data regarding reusable entities are required too, to implement the reuse strategy on asset components, facilitated by the disassembling one (Wong et al., 2012).

**Table 1. Mapping data families and CM strategies for ALM.**

| | *BoL* | | | | | | | *MoL* | | *EoL* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Technical requirements | Technical Drawings | User Manual | Assembly and Disassembly Instruction | Material Composition | Energy, Water, and Material Consumption for production | Commissioning strategy | Maintenance plan | Product Conditions | Product residual value | Reusable Entities | Energy, Water, and Material Consumption for regeneration | Remanufacturing plan |
| **Circular Design** | x | x | x | | | | x | | | | | | |
| **Cleaner Production** | | | | | | x | | | | | | | |
| **Disassembly** | | x | | x | | | | | | | x | x | |
| **Recycling** | | x | x | x | x | | | | x | x | | x | |
| **Remanufacturing** | | x | x | x | | | | | x | x | | x | x |
| **Resource efficiency** | | | | | | x | | x | | | | | |
| **Reuse** | | | | | | | | | x | x | x | | |
| **Servitization** | | | | | | | | x | x | | | | |
| **Waste Management** | | | | | x | | | | x | x | | | |

This overview on data for each CM strategy allows to get a preliminary map on the data requirements for sustainability-purposed goals. Nevertheless, the data are dispersed over diversified company repositories, including databases and EIS. Thus, section 3 reviews which are the relevant EIS in today industrial context, considering both the asset provider and asset user perspective.

## 3. ENTERPRISE INFORMATION SYSTEMS FOR ALM FOR CIRCULAR MANUFACTURING ENHANCEMENT

In the current industrial context, there is an heterogeneous ensemble of EIS the company could rely upon to manage their several business processes (El Kadiri et al., 2016). Thus, exchanging and sharing data appropriately, built upon EIS interoperability, is a relevant challenge which needs to be promoted for CM enhancement (Rajput and Singh, 2019). Indeed, EIS interoperability needs to be established at both technical and semantic level (Romero and Vernadat, 2016). The former implies to get conscious of the body of data that are needed to be exchanged, while the latter refers to the capability of EIS to talk each other consistently. Thus, while Table 1 gets the whole picture of data families' requirements, a reflection on company's EIS is also needed, having both the viewpoints, the one of asset provider (from a product perspective, i.e., PLM), and of the asset user (from an asset perspective, i.e., ALM).

### *3.1 EIS for ALM considering asset provider and user*

The asset provider (the OEM) could count on several EIS to manage the product lifecycle. Among these EIS for PLM, it is worth noting the following ones (Panetto et al., 2012):

- *Computer Aided Design (CAD)*: it is a computer system, composed of hardware and software, that supports and assists during the creation, configuration, and analysis, with eventual optimisation, of a product design.
- *Product Data Management (PDM)*: it is a system that collects all information regarding the product, from design, through production, to end-user support. As such, it is a multi-nature tool transversal to the others to guarantee data quality (Liu and Xu, 2001).
- *Enterprise Resource Planning (ERP)*: it is a system to holistically manage company business processes with special attention towards the financial transactions; also, they are extending in their functionalities sometimes overlapping with other EIS (Gupta and Kohli, 2006).
- *Manufacturing Execution System (MES)*: it is a system acting closer to the shop floor, managing all processes from production order release to the delivery of the realised final product.

As anticipated, these EIS form the ecosystem on which the asset providers primarily rely on, and, in this context, PDM plays as the backbone since it should convey all product-related data.

On the other side, when the complex industrial asset is installed in the asset user's facility, it is subjected to processes managed by other EIS. Namely, in addition to the already cited ERP and MES, which are generally present in companies, the following EIS become relevant for ALM:

- *SCADA (Supervisory Control And Data Acquisition)*: it is system connected to the most relevant industrial assets and equipment, and gather and store data for eventual further exploitation.
- *CMMS (Computerized Maintenance Management System)*: it is a system aiming at managing maintenance transactions, from maintenance scheduling to work order management. Recently, it is also called EAM (Enterprise Asset Management), even though the latter has usual a global perspective (Polenghi et al., 2020).

### *3.2 Intra- and inter-enterprise interoperability for CM strategies enhancement*

The identified EIS form ecosystems that serve to guarantee and optimise ALM process on the asset provider and asset user sides. Thus, for the ALM process to be managed at best, intra-enterprise interoperability is central. So, for the OEM, the connection between ERP-CAD-PDM-MES guarantees this process performing well; moreover several product-centric ontologies aim at guaranteeing interoperability, such as ONTO-PDM in (Panetto et al., 2012) or PRONTO (Giménez et al., 2008), complemented by others in scientific research (El Kadiri and Kiritsis, 2015); last but not least, several normative may be used as well, like the ISO 10303 or the IEC 62264. The ontologies are here addressed to as "asset provider ontology" and mainly come from PLM literature.

On the other side, the asset user could count on the set CMMS-SCADA-ERP-MES to support and optimise the management process of the asset lifecycle. Also, in this case, several initiatives foster the interoperability between these systems (Kiritsis, 2013). For example, ROMAIN (Karray et al., 2019) or the IOF-maintenance ontology (www.industrialontologies.org/maintenance-wg/) provide asset-centric ontologies for maintenance; to this end, the ISO 15926 is a relevant normative, combined with the ISO 13xxx family on condition monitoring and diagnostics of machines.

Again, for the matter of this research, the ontologies will be labelled as "asset user ontology" and mainly derive from maintenance and ALM literature.

Nonetheless, the intra-enterprise interoperability does not guarantee per se the full exploitation of all CM strategies. When referring to those strategies mostly confined in BoL, that is design and manufacturing of the product (later an asset when installed in user's facility), the intra-interoperability of PLM highly supports strategies like circular design, cleaner production, and resource efficiency. On the other side, servitization, e.g., maintenance service provided by the OEM to the user, must leverage upon data exchange between the two EIS ecosystems. This happens because maintenance service must rely on operating conditions and asset history that only the user's EIS could effectively provide. User's EIS ecosystem enables operating the asset efficiently (resource efficiency). Finally, the EoL-related CM strategies, that are disassembly, recycling, remanufacturing, waste management and reuse, should be enabled by a return of the asset history data from the user to the asset provider (assuming the latter in charge of the asset decommissioning). Also, in this case, inter-enterprise interoperability is fundamental to support EoL-related strategies for CM. Fig. 3 highlights the EIS ecosystems for the asset users and providers and the CM strategies for intra and/or inter-enterprise interoperability.

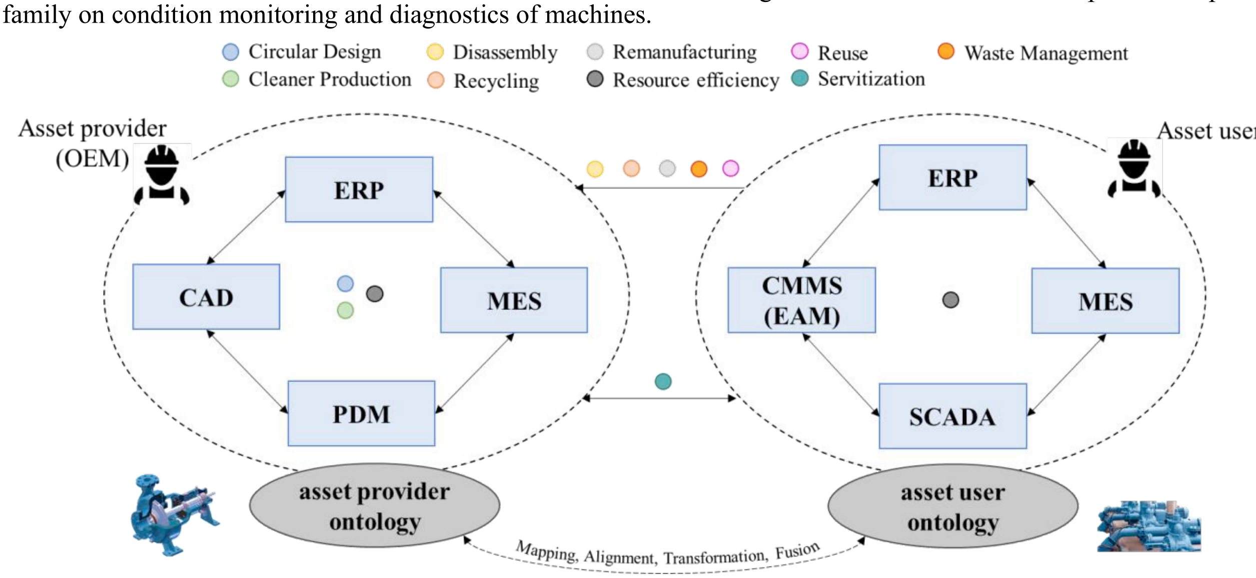


Fig. 3. EIS ecosystems of asset providers and asset users for CM strategies enhancement.

To enhance CM strategies based on proper data exchanges, both intra- and inter-enterprise interoperability are essential levers. Ontology engineering is advisable to this end:

1. the ontologies on which the EIS ecosystems are built upon should be firstly aligned for intra-enterprise interoperability (asset provider ontology and asset user ontology);
2. besides, these ontologies should be also integrated through semantic integration strategies, for guaranteeing CM-oriented inter-enterprise interoperability.

Both endeavours should leverage upon EIS semantic integration strategies (mapping, alignment, transformation and fusion) (Izza, 2009).

## 4. CONCLUSIONS AND FUTURE WORKS

The paper tackles information and data management for CM enhancement referring to the management of complex industrial asset, manufactured by an asset provider, and that is later operated by an asset user to realise business value. This change in the ownership implies data exploitation shortfalls. So, the needed data for each CM strategies, exploitable in ALM, are mapped starting from PLM paradigm. The PLM is chosen as starting point since it is more advanced in terms of both information and data management as well as CM. The mapping allows to understand that integration of several data sources is needed to guarantee proper CM exploitation. Therefore, a look towards the various EIS composing the company information systems stack is given. Furthermore, a preliminary analysis of the intra- and/or inter-enterprise interoperability requirements for each CM strategy is performed.

Based on these findings, future research must focus on guaranteeing intra-enterprise interoperability at first, creating what are here called asset provider ontology and asset user ontology, which should be unique and consistent. Thus, they should be built upon same ontological commitment (almost, the same foundational ontology), while reusing already available ontologies. Secondly, these ontologies should be integrated to guarantee inter-enterprise interoperability.

To this end, the works done in CHAMP (Coordinated Holistic Alignment of Manufacturing Processes, https://github.com/NCOR-US/CHAMP) and IOF (Industry Ontologies Foundry) (Wallace et al., 2018) are of paramount importance to guarantee the creation of coherent and consistent ontological models that may finally lead to overcoming existing interoperability issues. Aligned with these initiatives, the IFAC TC 5.3 (tc.ifac-control.org/5/3/) on "Integration and Interoperability of Enterprise Systems" fosters research in enterprise integration, especially for PLM. From a more business and process viewpoints, the IFIP WG 5.7 SIG on PLM/ALM (www.ifipwg57.org/special-interest-groups/) is looking after solutions for the integration of the lifecycle management processes. These groups should also elaborate over the ethical issue of sharing data between asset providers and users in relation to privacy and cybersecurity.

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