# Information as a key dimension to develop industrial asset management in manufacturing



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## Abstract

**Purpose** – The purpose of this work is to investigate industrial asset management (AM) in manufacturing. After depicting gaps for AM in this sector, the role of information as a key dimension is considered to realise a summary of challenges and advices for future development.

**Design/methodology/approach** – The work is grounded on an extensive systematic literature review. Considering the eligible documents, descriptive statistics are provided and a content analysis is performed, both based on a sector-independent normative-based framework of analysis.

**Findings** – AM principles, organisation and information are the dimensions defined to group ten areas of interest for AM in manufacturing. Information is the major concern for an effective AM implementation. Moreover, Internet of Things and big data management and analytics, as well as data modelling and ontology engineering, are the major technologies envisioned to advance the implementation of AM in manufacturing.

**Research limitations/implications** – The identified challenges and advices for future development may serve to stimulate further research on AM in manufacturing, with special focus on information and data management. The sector-independent normative-based framework may also enable to analyse AM in different contexts of application, thus favouring cross-sectorial comparisons.

**Originality/value** – Industries with higher operational risk, like Oil&Gas and infrastructure, are advanced in AM, while others, like some in manufacturing, are laggard in this respect. This literature review is the first of a kind addressing AM in manufacturing and depicts the state-of-the-art to pave the way for future research and development.

**Keywords** Asset management, Literature review, Framework, Information, Maintenance, Manufacturing, Data, Life cycle

**Paper type** Literature review

## 1. Introduction

Industrial asset management (AM), intended as an integrated methodology to optimise the management of the assets along the life cycle, is becoming more and more popular in the industrial world, bringing the focus on industrial assets (equivalently, physical assets) besides financial, human, information and intangible assets. AM is currently defined as "*the coordinated activities of an organization to realize value from assets*" (ISO 55000, 2014) and integrates classic operations viewpoints, built on production and maintenance management (which has been given a more strategic role than before (Gomes *et al.*, 2020)), with a major focus on a long-term strategic perspective (El-Akruti and Dwight, 2013; Ruitenburg *et al.*, 2017).



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Oil&Gas and infrastructure industries were the first adopting AM, driven by safety and quality, and pushed by overwhelming regulatory requirements (Lloyd, 2010). In particular, Oil&Gas needs to guarantee the top safety standards since its operation is highly risky (Holland *et al.*, 2005). Companies in manufacturing are instead showing different approaches towards AM depending on their inherent operational risk; in general, there is not a homogeneous maturation of AM in manufacturing industries. However, some companies are today scaling worldwide and, even though characterised by low risk, are looking at AM as a lever to manage their assets at best, to be competitive (Campbell *et al.*, 2016). AM helps in orchestrating not just maintenance and operation phases of the assets but also the design and commissioning, thus the entire life cycle (Institute of Asset Management, 2015). The growth of technological complexity is another reason to better coordinate asset-related decisions through their life cycle in manufacturing facilities (Kulvatunyou *et al.*, 2019).

Notwithstanding the growing interests, clear guidelines to embed AM in industrial organisations and processes are still poorly discussed (Roda and Macchi, 2018). Due to the wide scope of AM implementation, researchers and practitioners are constantly involved in AM adoption or improvement from different perspectives, either focused on single sectors or more generically addressing specific issues relevant for AM. Furthermore, few authors focus on AM in manufacturing, and reviews in the last decade focus on other sectors, e.g. (Schraven *et al.*, 2011) whose focus is on infrastructure. Looking at information-centric reviews for AM, a survey of case studies performed by (Akofio-Sowah *et al.*, 2013) showed a gap in data management, proving that maintenance contractors do not rely on AM or maintenance-specific tools as the CMMS (computerized maintenance management system), but on generic software. (Khuntia *et al.*, 2016) remark on the importance of data management in maintenance and risk management activities to enable AM. Recently, (Petchrompo and Parlikad, 2019) propose a general review on AM, which points out information and data management as relevant issues to enable AM to effectively cover the dependencies of components, fleets and portfolios.

Considering the need to pursue the adoption of AM in the manufacturing sector at large, it is worth remarking that a systematic study on AM in this scope is not apparent from the published recent literature. This brings us to the following research questions this review is willing to answer:

(1) What is the state-of-the-art of scientific research about AM in manufacturing?

(2) What are the gaps recognised in the literature about AM in manufacturing?

The presumption is that information and data management remains a relevant issue also for manufacturing companies, and a systematic study of literature is proposed to point out the main dimensions and related areas of interest, based on which challenges and advices for future development of AM in manufacturing can be discussed.

The structure of the paper is as follows. Section 2 describes the research methodology and its application. Section 3 presents a descriptive analysis of the eligible documents, whose content is analysed in section 4. Section 5 summarises the main challenges and advices in information and data management for AM in manufacturing, while section 6 draws some conclusions for AM in general.

## 2. Research methodology

The adopted methodology in this research work is the systematic literature review (SLR). It is decomposed into four main phases (Brereton *et al.*, 2007): (1) definition of a framework, (2) definition of the research protocol, (3) systematic review implementation and (4) research content analysis.

*2.1 Framework*

The development of a sector-independent normative-based framework stems from the need of having an overview of the dimensions and areas of interest within the AM scope, and of having a structure through which the literature can be analysed. The creation of the framework was an iterative process that involves the analysis of both the scientific literature and the ISO 5500x that complement each other. The latter is crucial to identify those dimensions and areas that should be considered while implementing a suitable AM system. The former is relevant to qualify the areas of interest listed in Table 1, along with a description; indeed, the table includes the areas for which correspondent scientific works could be identified during the iterative process.

The different areas of interest can be grouped in higher-level dimensions:

(1) Areas #1 Life cycle, #2 System, #3 Risk, #4 Value orientation provide the principles to follow when dealing with AM decision-making, and a common background for every research or implementation of an integrated AM decision-making process (Roda and

| Areas | | Description | Literature references |
|---|---|---|---|
| #1 | Life cycle orientation | refers to the assessment of the asset-related decisions against the short-, medium- and long-term | Roda and Macchi (2018), Choobineh and Mohagheghi (2016) |
| #2 | System orientation | deals with the need to consider the system as a whole, thus including interconnections and interdependencies between assets | Roda and Macchi (2018), Davé *et al.* (2017), Roda *et al.* (2016) |
| #3 | Risk orientation | considers the management of risk within AM, which is recognised as a key-driver (together with cost and performance) for an effective AM system | Roda and Macchi (2018), Niekamp *et al.* (2015) |
| #4 | Value orientation | deals with the need to create value from assets, thus pushing in the direction of assessing the systems and fleet of assets and the assets portfolio against value, rather than solely an economic perspective | Roda *et al.* (2016), Roda and Macchi (2016), Gibbons *et al.* (2012) |
| #5 | Company culture | collects all the knowledge, competencies, skills and attitude of the organisation towards AM concepts, definitions and application | Kangilaski and Shevtshenko (2017), Rippel *et al.* (2016) |
| #6 | Organisational structure | considers how the company is organised in terms of departments, functions and units, for the translation of corporate objectives into technical and financial decisions for AM | El-Akruti and Dwight (2013), Kangilaski and Shevtshenko (2017) |
| #7 | Multidisciplinary orientation | involves the interaction between different organisational units, avoiding the common "silo approach" | El-Akruti and Dwight (2013), Golightly *et al.* (2017) |
| #8 | Information management and integration | includes all the issues related to how to manage information within the organisation and how to integrate it to support asset-related decisions | Amadi-Echendu *et al.* (2010), Kangilaski and Shevtshenko (2017) |
| #9 | Data to information transformation | deals with the extrapolation of useful information from raw data from the shop-floor | Amadi-Echendu *et al.* (2010), Golightly *et al.* (2017), Campos *et al.* (2017) |
| #10 | Data collection | considers data gathering from different sources | Amadi-Echendu *et al.* (2010), Campos *et al.* (2017) |

**Table 1.** Areas of interest used to map the literature review

Macchi, 2018); for this reason, they are collected under the dimension of “AM Principles”;

(2) Areas #5 Company culture, #6 Organisational structure, #7 Multidisciplinary orientation are related to the organisation in a broad sense; they refer to the culture of managers and employees, the organisational structure and the orientation towards a cross-functional decision-making process, to support the implementation of AM; these areas are then grouped within the “Organisation” dimension;

(3) Areas #8 Information management and integration, #9 Data to information transformation, #10 Data collection deal with the support provided to the operation of the assets and the decision-making process within AM; they all consider information and data management, and, accordingly, they are gathered under the dimension of “Information”.

*2.2 Research protocol*

The first step in the configuration of the literature search was to plan the eligibility criteria:

(1) Only English-written documents with full text available.

(2) Peer-reviewed journal papers and conference papers.

(3) Papers dated 2008 forwards, since it is the year when the second revision of the PAS 55 (precursor standard for the ISO5500x) was issued, introducing a common vocabulary of AM.

The definition of suitable eligibility criteria was followed by the selection of the appropriate keywords and Boolean operators to span the AM topic in the literature, as presented in Table 2.

The adopted search technique involved the three main parts of a document: title, abstract and keywords. The addressed databases were Scopus and Web of Science (WoS), relevant for the industrial engineering sector.

*2.3 Systematic review implementation*

The literature search follows a process aligned to what most of the SLR includes (e.g. Sansone *et al.*, 2017): duplicates removal, eligibility criteria application, title and abstract screening, full-text reading and snowball analysis. The literature search process is summarised in Figure 1, which allows starting from 1,749 documents and finally comes up with 85 documents relevant to the research questions.

A high presence of the *Asset Management* term before 2008 is evident, but its meaning is usually limited: many authors used AM only to mean “to manage assets” within a maintenance-related scope, which does not lead to the complete sense of AM.

**Table 2.** Keywords for the literature review

| | Keywords | |
|---|---|---|
| | AM-related* | Sector-related |
| ↑ OR ↓ | “Asset Management”<br>“Asset Lifecycle Management”<br>“Asset Life Cycle Management” | Manufacturing<br>Production |
| | ← AND → | |

**Note(s)**: *“Asset Lifecycle Management” and “Asset Life Cycle Management” are introduced as synonyms of “Asset Management”

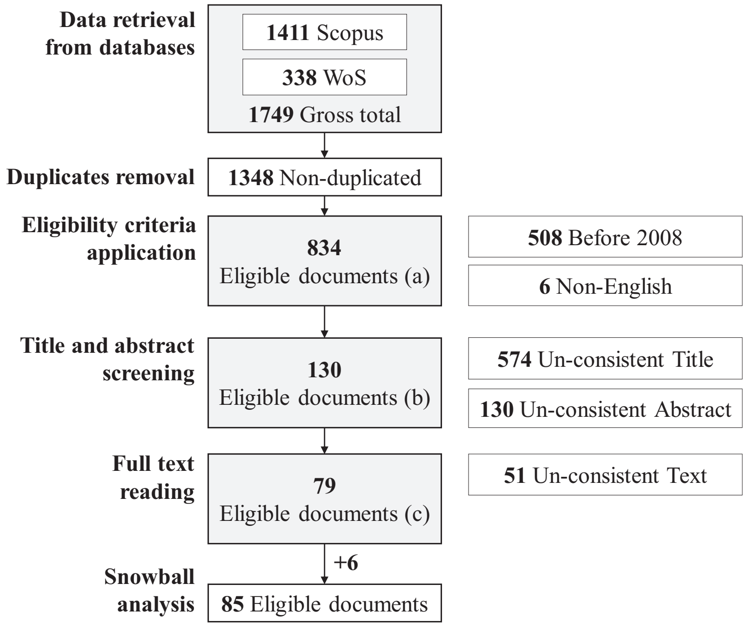


**Figure 1.**
Literature search process

To shed light on how the title and abstract screening were performed, Table 3 summarises the agglomerated categorisation based first on the title and then on the abstract, according to the classification by EU community (Eurostat, 2008).

The screening is performed by firstly looking at the title to get evidence on the sector. In case the title is not self-explicative, the paper is labelled as addressing manufacturing, and later checked in the abstract screening. In this step for the documents belonging to manufacturing (sector C), the abstract is read to confirm or not the classification made before.

It is worth noting how sector M initially plays a central role. Indeed, this sector collects all the research works not focused on specific sectors but dealing with general research. Also, sectors B, D and E represent sectors where AM is extensively introduced as shown in the statistics of Table 3.

As a result, 79 documents survived the literature search process (eligible documents (c) in Figure 1); this number is incremented by 6 after the snowball analysis, so that 85 eligible documents were finally taken for the analysis. Conference papers are the majority, and this may feed the growth of journal papers in the next years (Figure 2).

## 3. Descriptive analysis of eligible documents

The content of the 85 eligible documents allows depicting the state-of-the-art of the scientific research about AM in manufacturing. In the following sub sections, the documents statistics and the topics addressed are described.

### *3.1 Documents statistics*

The papers show that theoretical research is the most widespread methodology, as shown in Figure 3. It brings to the definition of frameworks for different objectives: driving the implementation of an AM system (Roda and Macchi, 2018), mapping the enablers to support asset-related decisions (Kangilaski and Shevtshenko, 2017) and pushing towards optimisation in the energy and asset management (Choobineh and Mohagheghi, 2016).

| Sector classification | Title screening | | Abstract screening | |
|---|---|---|---|---|
| A – Agriculture, forestry and fishing | 5 | 1% | 2 | 1% |
| B – Mining and quarrying | 136 | 16% | 48 | 18% |
| *C – Manufacturing* | *260* | *31%* | *130* | *50%* |
| D – Electricity, gas, steam and air conditioning | 68 | 8% | 17 | 7% |
| E – Water supply; sewerage, waste management and remediation activities | 25 | 3% | 0 | 0% |
| F – Construction | 28 | 3% | 4 | 2% |
| G – Wholesale and retail trade; repair of motor vehicles and motorcycles | 0 | 0% | 0 | 0% |
| H – Transportation and storage | 25 | 3% | 9 | 3% |
| I – Accommodation and food service activities | 1 | 0% | 0 | 0% |
| J – Information and communication | 34 | 4% | 8 | 3% |
| K – Financial and insurance activities | 26 | 3% | 1 | 0% |
| L – Real estate activities | 1 | 0% | 0 | 0% |
| M – Professional, scientific and technical activities | 157 | 19% | 37 | 14% |
| N – Administrative and support activities | 8 | 1% | 1 | 0% |
| O – Public administration and defence; compulsory social security | 5 | 1% | 0 | 0% |
| P – Education | 3 | 0% | 0 | 0% |
| Q – Human health and social work activities | 7 | 1% | 2 | 1% |
| R – Arts, entertainment and recreation | 11 | 1% | 0 | 0% |
| S – Other service activities | 0 | 0% | 0 | 0% |
| T – Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use | 0 | 0% | 0 | 0% |
| U – Activities of extraterritorial organisations and bodies | 0 | 0% | 0 | 0% |
| NA (including documents with no specified details) | 34 | 4% | 1 | 0% |
| TOTAL | 834 | 100% | 260 | 100% |

**Table 3.**
Screening statistics per sector

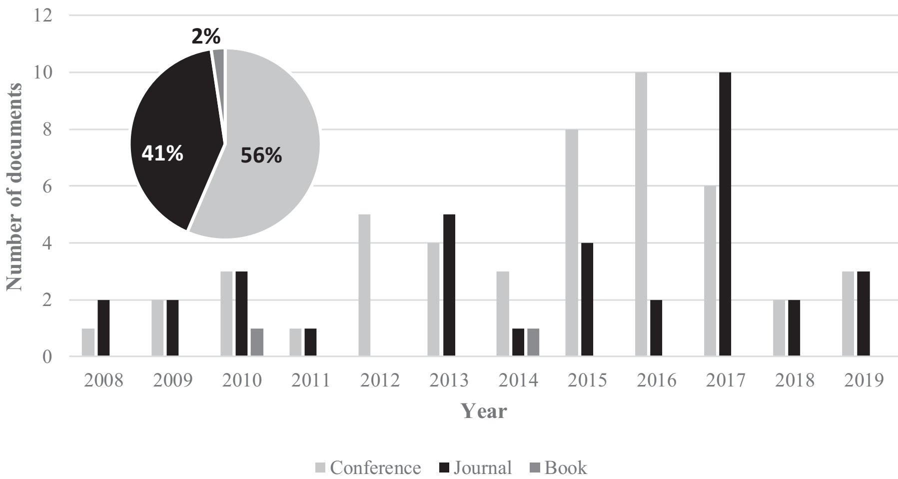


**Figure 2.**
Eligible documents biographical statistics

*3.2 Addressed topics statistics*

The 85 documents were mapped according to the developed framework as shown in Figure 4, considering different levels: the aggregate level statistics about the dimensions are shown in the top, while the detailed statistics about the areas of interest are presented as pie charts.

At the aggregate level of analysis, the information dimension is the most addressed one by the authors of the eligible documents (accounting for 51%). Moreover, the information

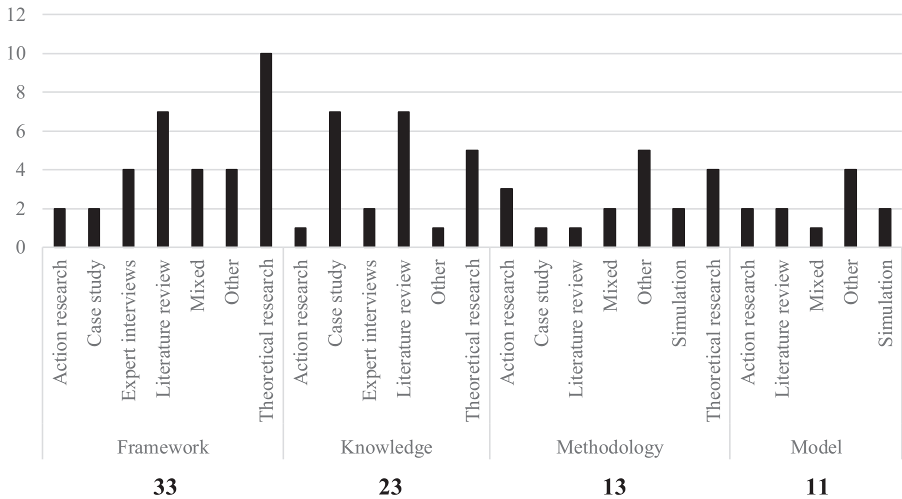


**Figure 3.** Contributions and research methodologies adopted in the 85 documents

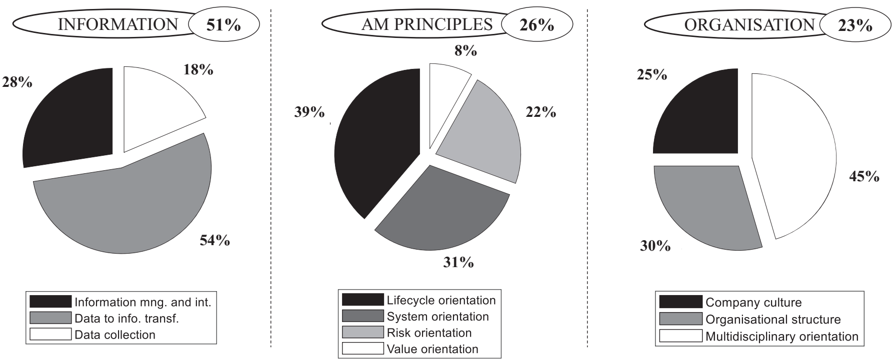


**Figure 4.** Aggregate and detailed-level statistics (see Supplemental material for details)

dimension shows an ever-increasing interest in the scientific literature over the years, as demonstrated in Figure 5. More in detail, Figure 4 remarks that "Data to information transformation" is the primary concern (54%) when dealing with AM in manufacturing, followed by "Information management and integration" (28%) and "Data collection" (18%).

The dimension of AM principles is dominated by the "Lifecycle orientation" (39%), which remarks the fact that AM should look at the life cycle of an asset, followed by "System orientation" (31%), "Risk orientation" (22%) and "Value orientation" (only 8%).

Looking at the organisation dimension, it is possible to see that "Multidisciplinary orientation" (45%) is well treated in the literature, underlying the importance of the interaction between different departments within the organisation. "Organisational structure" (30%) and "Company culture" (25%) are almost equally treated.

## 4. Research content analysis

The authors of the eligible documents underline different gaps, intended as identified areas of interest to be further investigated, along with the corresponding overarching goal

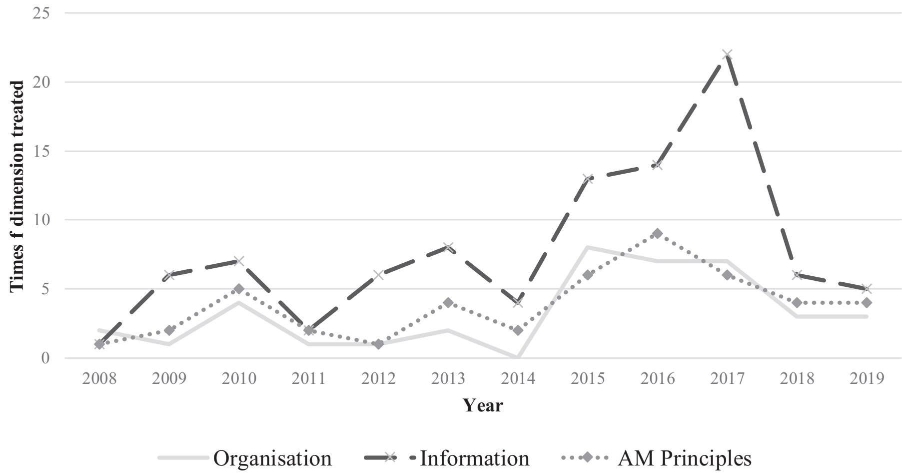


**Figure 5.**
AM dimensions: time trend

(see Table 4). The analysis shows that the current interest is diversified, as it is evident from the number of documents dealing with each area.

To provide a better overview of the highlights in the literature, a double-axis chart is realised (Figure 6). On the horizontal axis, the number ($x$) of papers identifying each area of interest as a gap is shown; on the vertical axis, the number ($y$) of papers addressing that

**Table 4.**
Recognised AM gaps in the literature

| Dim. | Area of interest (as gap) | Overarching goal | Doc. count |
|---|---|---|---|
| Information | #8 Information management and integration | The correct integration and suitable management of the information related to assets to make it available when and where needed to make appropriate decisions | 17 |
| | #9 Data to information transformation | The suitable exploitation of data to create reliable information on which to make appropriate asset-related decisions | 9 |
| AM principles | #2 System orientation | The understanding of the interdependencies between different parts of the same system, through proper modelling (to understand how decisions on one part have consequences overall) | 7 |
| | #1 Life cycle orientation | The assessment of the impact of an asset-related decision in the long-term, considering all of the life cycle stages (from beginning to end of life) | 4 |
| | #4 Value orientation | The creation of value from assets (performance, cost and risk), derived from suitable AM decision-making process | 3 |
| | #3 Risk orientation | The management of risk to support asset-related decisions, making them reliable against uncertainties | 2 |
| Organisation | #7 Multidisciplinary orientation | The coordination and interaction between different organisational functions to favour asset-related decisions | 4 |
| | #5 Company culture | The commitment of all persons involved in the AM decision-making process to the goal of realising value through long-term decision-making | 1 |

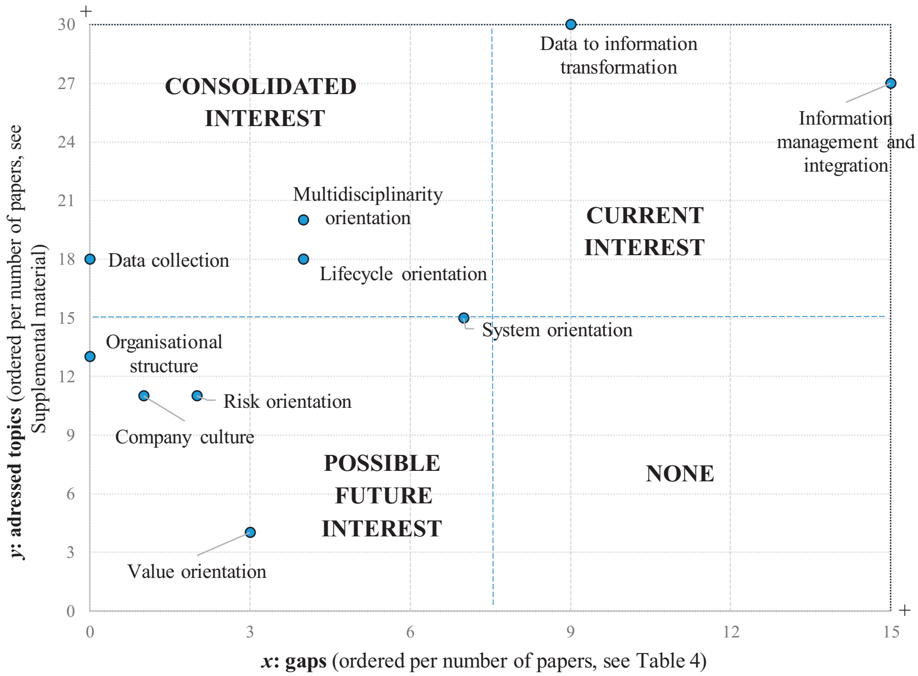


**Figure 6.**
Mapping the areas of interest

specific area of interest is reported. The chart is divided into four quadrants as a proxy of the interest: *consolidated interest* for well-addressed areas (high $y$), almost consolidated as a few gaps are indicated (low $x$); *current interest* for well-addressed areas (high $y$), not yet fully understood due to extant gaps (high $x$); *possible future interest* for areas appearing not enough mature today in literature (low $y$), thus showing just a potential room for improvement (low $x$); *none*, where the two situations ((high $x$) vs. (low $y$)) cannot in principle withstand together.

### *4.1 Content analysis for the areas of interest*

The dimensions are now analysed, looking at the contents highlighted by literature for the most relevant areas of interest according to Figure 6.

(1) System orientation is envisioned to be of *possible future interest*. In this perspective, IoT (Internet of things) is currently investigated for industrial assets through the concept of SIoIT (Social Internet of Industrial Things), remarking that "*there remains a lack of research on linking the performance of a single machine to the performance of other machines, as well as the whole system*" (Li and Parlikad, 2016). Aligned with this statement, Roda *et al.* (2020) confirm that a clear understanding of the system is missing also in total cost of ownership applications; this influences the data collection, most of the time limited to the life cycle management of single assets.

(2) Even if life cycle orientation results as a *consolidated interest*, many authors stressed the importance of strengthening this principle, also because it relates to system orientation. Indeed, system orientation leads to a modelling capability to provide a formalisation of the interdependencies between assets and of the behaviour of the assets themselves along their life cycle (Roda *et al.*, 2016); this enables to test the consequences of asset-related decisions in the medium and long term. All in all, the

joint development of both areas of interest in the dimension of AM principles is an opportunity.

(3) The multidisciplinary orientation is stated as the most important gap for the organisation dimension, and it is a *consolidated interest*. Indeed, Dongen (2015) remarks how AM and maintenance require a multidisciplinary approach to optimise the practices in AM decision-making. In Ruitenburg *et al.* (2017), the multidisciplinary approach is also remarked as central: information and knowledge are dispatched within different organisational functions, inside and outside the company, to support decisions.

(4) Information management and integration and data to information transformation are *current interest* for the information dimension. In Petchrompo and Parlikad (2019), data interconnection is defined as a major gap. Interconnecting data (a matter of integration) habilitates the possibility to understand the behaviour of assets through real-field data from single assets, to finally support an approach to decision-making that is both data and value-driven. To this end, value stream mapping (VSM) may be adopted to analyse data needs at both macro and micro level to avoid information waste along the different maintenance processes (Marttonen-Arola and Baglee, 2019). Bousdekis *et al.* (2015) underline the relevance of having a suitable information space on top of which building prognostics applications of AM, by integrating several heterogeneous sources. Nowadays, the development of an architecture to manage big data requires to invest in IT and to integrate information to manage decision-making (Campos *et al.*, 2017), to fully exploit the data analytics capabilities (to transform raw data into information useful for the organisation) (Macchi *et al.*, 2018).

(5) As a cross-dimensions reflection, it is worth remarking that information management and integration is particularly related to multidisciplinary orientation. Indeed, to build an integrated platform to share and exchange information and data favouring the development of a multidisciplinary approach in AM and, at the same time, pushing towards the multidisciplinary orientation for asset-related decision-making asks for information integration between different departments in the organisation. All in all, the two areas of interest are mutual enablers, and their joint development appears a necessity for their reinforcement.

### *4.2 Concluding remarks on literature findings*

The performed SLR on AM in manufacturing shows an ever-increasing interest, especially about information and data management. Nevertheless, the literature has also proven to be dispersed, and this review provides insights on the core AM dimensions that, in a unique framework, enable to identify areas of interest requiring further investigation, highlighted in Figure 7.

Based on the literature findings, most of the identified gaps are related to those areas of interest dealing with an integration concept in a broad sense, including the assessment of decisions for their impact in the long-term (life cycle orientation), the relationships between different assets for the system of assets in its entirety (system orientation) and the interaction between different organisational units (multidisciplinary orientation).

Particularly, while being an enabler for integration, the information dimension is prominent to develop AM in manufacturing. The transformation of data sourced from the assets in the shop floor into relevant information and, in general, the management and integration at different levels of the enterprise-wide solutions, including data to information transformation as well as information management and integration, play a key role in the identified gaps. Therefore, section 5 focuses on information dimension: it is a current interest

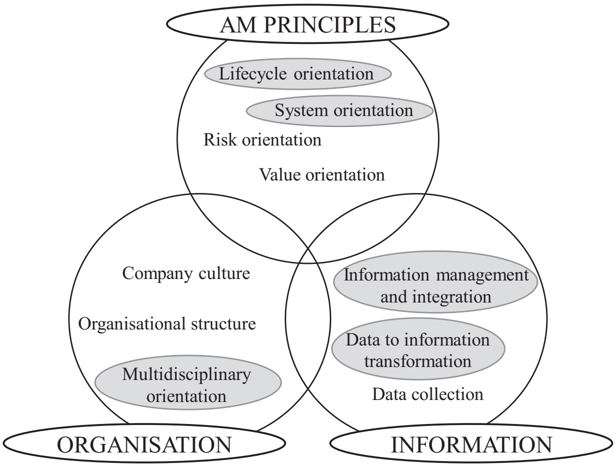


**Figure 7.**
Overview on AM gaps (in grey, those of major concern according to literature findings)

according to the results of Table 4; furthermore, its centrality in guaranteeing integration is a lever also to address the other identified gaps.

## 5. Challenges and advices for information and data management in AM

The need to stress and highlight challenges and advices for information and data management comes from the key role that it plays, according to the performed SLR, in supporting and improving the AM decision-making. Nonetheless, when talking about information, the connection with current available technologies is advisable. Therefore, in this section, a review of the information and data management process (data collection, data to information transformation and information management and integration) is proposed, in light of technologies identified through a selected review of recent literature on AM and, as a complement, on maintenance with strategic perspective. The analysis is complemented by authors' industrial experience in the field.

Hence, Figure 8 summarises the areas of interest associating a criticality to each of them according to the results in section 4, identifying relevant managerial and technical challenges from selected literature, as well as finally mapping enabling technologies leading to an IT

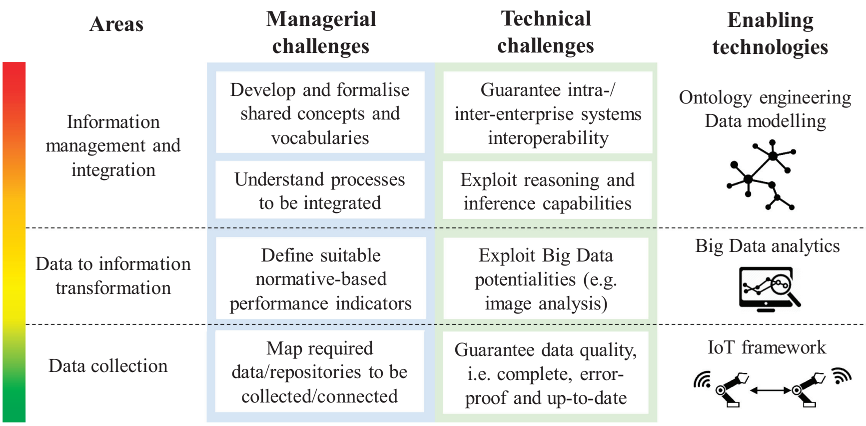


**Figure 8.**
Managerial and technical challenges, with envisioned enabling technologies, for advances in AM in manufacturing (the coloured bar shows the perceived criticality for AM, where red is high criticality and green low criticality)

ecosystem supporting the AM decision-making. Overall, Figure 8 proposes an overview of authors' vision, while details for each area are provided hereinafter.

*IoT as a necessary foundation to advance the AM practice*. Internet of Things (IoT) has been progressively regarded as an effective framework to adopt and improve AM (Gulati and Kaur, 2019), with special attention towards SIoIT (Social Internet of Industrial Things) for manufacturing assets (Li and Parlikad, 2016). It provides the necessary IT infrastructure as foundation for advanced connectivity of industrial assets. It is then an enabler to gather data from different sources (sensors, controllers, etc.), useful to finally lead to new data available about the asset operations. IoT by itself does not imply peculiar challenges for AM as it is already a result of the comprehensive trend of digital transformation in manufacturing (Borangiu *et al.*, 2019); nevertheless, it is a mandatory step to progress in further achievements, and some challenges may be also underlined:

(1) Guarantee data quality (i.e. complete, error-proof and up-to-date) by the IoT is mandatory to avoid misleading and erroneous data being later transformed into indicators for decision-making.

(2) Map required data/repositories to be collected/connected is fundamental since IoT must be guided towards the right connections and data retrieval beforehand.

*Big data management and analytics to support reliable information for the AM decision-making*. High volume and variety of data are collected from the assets operations, thanks to the IoT framework; in particular, different types of asset-related data (condition monitoring and event data) are used to assess the assets health, operations and environments, and to manage them in view of their impacts (Cheng *et al.*, 2018). Thus, it is relevant to put emphasis on analysing the right data to make the right decisions. To this end, various challenges, related to the generation of value from multiple data, should be met in the future development. Therefore, firstly, the engineering of features is advisable, as assets health and performance indicators, significant for the goal of each analysis, both consider operational (Niu *et al.*, 2010) and strategic decision-support (Yunusa-Kaltungo and Labib, 2020). Besides, the definition of an IT architecture for a balanced big data analytics is also a major advice: decentralised and centralised big data analytics should be balanced to obtain accurate information for performance ratings and collaborative prognostics in a fleet of assets (Lee *et al.*, 2015). Thus, current challenges in the area of data to information transformation reside in:

(1) Exploit big data potentialities, for example, image analysis and text analytics, for advanced machine prognostics and information extrapolation from unstructured data for maintenance optimisation.

(2) Define suitable normative-based performance indicators that enable internal consistency of performance measurement between departments and external benchmarking for self-improvement.

*Data modelling and ontology engineering for seamless information management and integration to support AM decision-making*. Information is central to provide effective decision-making to suitably manage the assets for company business. To this regard, the AM system should enable the capabilities to manage the information, guaranteeing the interoperability of different decision-making processes and the organisational units involved. Data modelling and ontology engineering are advisable to this end. Data models allow formalising the required informative content at every step of the processes, providing support for IT ecosystem (re)planning in the AM system (Polenghi *et al.*, 2019). Ontologies empower what is defined in data models by means of reasoning and inference-making capabilities (powerful when scaling up), leveraging on a common and shared vocabulary; this is especially relevant to automate data processing across dispersed informative content, which is the case of AM (Kiritsis, 2013). Accomplishing these developments needs further work on both the managerial and technical side:

(1) Guarantee interoperability between inter-/intra-enterprise information systems for seamless integration of internal departments and along the supply chain.

(2) Understand processes to be integrated, to support and drive interoperability effort and resources of the company with a long-term perspective.

(3) Develop and formalise shared concepts and vocabularies to guarantee not only technical but also semantic interoperability of internal departments and with external companies.

(4) Exploit reasoning and inference-making capabilities to augment the information content stored in various repositories.

The three areas are relevant for future works in the research agenda and are related to problems in practice. From this perspective, in authors' understanding from industrial experiences, it is relevant to have an architectural perspective of the IT ecosystem a company is developing, to support the entire AM decision-making with attention on the required functionalities at each control level, from operational to strategic control level. The market's offer from leading software houses reflects this evolution, evolving from a one-fits-all and traditional solution for maintenance and AM, that is, the CMMS. Nowadays, the layered approach consists of the functionalities of EAM (enterprise asset management) as well as of APM (asset performance management): the EAM comprises traditional maintenance management functionalities, for example, work order, inventory and procurement management and general purpose ones, such as human resources management (Campbell *et al.*, 2016); the APM includes functionalities like risk management and assets/asset system modelling (Polenghi *et al.*, 2020), thus allowing long-term strategic management. Furthermore, aligning with the assets strategies due to APM, new cloud-edge computing architecture are being adopted to develop an operational intelligence through advanced systems for predictive maintenance (Ferreira *et al.*, 2017).

Overall, the newly emergent structure leads to an advanced IT ecosystem (Baron, 2018). As such, it promotes the implementation of an effective AM strategy through enterprise-wide solutions, particularly conceived for asset-intensive organisations requiring safe and reliable operations at lower costs.

## 6. Conclusions

This research work stems from the increasing interest companies and researchers are showing towards AM as integrated methodology to govern the entire portfolio of industrial assets (physical assets) along their life cycle at best. Even though it saw first conceptualisations in the late 90s, AM is only recently showing potential to every industrial sector, including manufacturing. However, manufacturing at large is still a laggard in AM adoption; therefore, an overview of what has been done so far and what is still seen as gap were deemed useful to favour further reflection on the possible future development.

The application of the SLR supports the definition of the state-of-the-art of the scientific knowledge by leveraging upon a sector-independent normative-based framework that identifies three main dimensions of AM, namely information, organisation and AM principles. The first dimension includes researches focused on information and data management as support for improved decision-making; the second dimension involves academic works dealing with organisation structure, company culture and cross-functional decision-making; the third dimension embraces scientific researches centred on enhancing adoption of specific AM-related principles for integrated decision-making. The SLR allows also to identify the main gaps according to extant scientific knowledge, and, out of the three dimensions, information is recognised as the most critical one, especially in the areas of information management and integration, and data to information transformation. Herein, data modelling and ontology engineering are fostered to support the former area, while big data management and analytics is a core lever in the latter.

The limitation of this work resides in the time span defined in the research protocol. The analysis sticks to the definition of AM starting from normative (ISO 5500x, PAS 55), while looking at scientific works dated 2008 backwards (before PAS 55) may have biased the research since AM was also intended within a narrow scope, that is, "to manage assets" within a maintenance-related scope, which does not lead to the complete sense of AM. Moreover, the most recent literature could bring to light current trends of AM and its motivations, such as when looking at AM as a lever for worldwide spread of large-scale manufacturing companies. Indeed, gaps, challenges and advices discussed for future development are inherently related to this scale.

A second limitation of this work is that the identification of gaps and challenges relies on the scientific works collected in the literature review; it does not imply that the current ongoing problems experienced in practice are fully covered. Thus, it should be relevant to complement the results of this work with empirical researches.

In future research, it is advisable to extend the analysis to researches on AM before 2008, in order to exploit the past discussion to confirm the gaps and challenges identified in this work. Furthermore, additional work is required to analyse the evidence gathered during collaborative projects that, as action researches, should give empirical proofs of the advices theorised for the development of AM in manufacturing. Doing these researches, it will be possible to study the implications of information and data management on the implementation of AM principles (in particular, system and life cycle orientation) in the decision-making processes. This is clearly relevant in order to complete the scientific perspective provided by the published papers with the evidence gained within the currently ongoing manufacturing practice.

As final suggestion, the normative-based framework might be used for similar analysis in different sectors, so as to gather evidences from field of the gaps in each of them, useful for cross-comparisons in the development of AM discipline.

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## Supplemental material

The supplemental material is available in the online version of this article.

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