Towards a Smart Manufacturing Maturity Assessment Framework: A Socio-Technical Perspective

Lei Yue 1*, Pengfei Niu 1, Yifang Fang 2 and Zhonghua Han 3, 4

1 Sensor and Network Control Center, Instrumentation Technology and Economy Institute, Beijing 100055, China
2 Information Center, Instrumentation Technology and Economy Institute, Beijing 100055, China
3 Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China
4 Faculty of Information and Control Engineering, Shenyang Jianzhu University, Shenyang 110016, China
* Corresponding author’s e-mail: yuelein@126.com

Abstract. Researchers of information technology (IT) have often suggested that there is no clear relevance between the IT investment and return on investment (ROI) of enterprises. This phenomenon is called “productivity paradox”. However, research on smart manufacturing capability maturity did not reflect empirically the fact that enterprises rarely benefit from information systems. Therefore, the aim of this article attempts to explore how humans and technologies are related and propose a smart manufacturing maturity assessment framework that can reveal the interaction between humans and technologies. This research addressed two questions, (a) what domains can be identified for smart manufacturing, and (b) how to harmonize all of the technical and social factors affecting maturity and benefits. A complicated concept “socio-technical system” was surveyed for interpreting how enterprises benefit from technologies. Results of this study showed a smart manufacturing maturity assessment framework from the socio-technical perspective. As an explanation, the understanding of manufacturing operations management (MOM) capability maturity model (CMM) within the framework in the case study and its results were presented. To conclude, this study may be regarded as a meta-model or reference model for specific maturity models, as well as has the merit of offering valuable insights into the maturity assessment.

1. Introduction
Smart manufacturing is the primary driving force for the innovative development of manufacturing industry and the main pathways of the manufacturing industry transformation and upgrading. This new manufacturing paradigm is characterized by deep integration of emerging information communication technology (ICT), operation technology (OT) and manufacturing technology (MT). However, there is no ready-made experience to apply directly over the past hundreds of years of industrial development. All the world’s manufacturing powers are in the progress of exploring their own industrial transformation and upgrading pathways. So far, the ecological environment promoting the development of smart manufacturing is forming. Some progress has been made in policy support,
standard establishment, integrator cultivation, smart equipment and industrial software supply over the world.

In this situation of global smart manufacturing transformation and upgrading, more and more manufacturing enterprises are implementing a smart manufacturing transformation and upgrading strategy, and a large amount of emerging ICTs, OTs and MTs are adopted to improve their various performance aspects. Though some manufacturing enterprises have used a lot of smart equipment, they were not as economical as people thought. Some enterprises have introduced information systems such as manufacturing execution system (MES) and enterprise resource planning (ERP) system, but they have not benefited from these systems as expected. In other cases, enterprises have collected and stored huge data, yet it is difficult to discover the valuable information and knowledge[1].

In the last two decades, many advances have been made in the area of benefits from information systems. Shang & Seddon (2000) have proposed a framework for classifying the types of benefit that enterprises can achieve by using ERP systems based on analyzing data from ERP vendor success stories and interviews with ERP cases[2]. Numerous studies (Esteves, 2009; Staehr, 2010; Staehr, 2012) have focused on a realisation roadmap for ERP usage and achievement of business benefits from ERP systems during different implementation phases based on Shang & Seddon’s results[3-5].

Besides above, a lot of research works have been done in the field of smart manufacturing capability maturity assessment to help enterprises position themselves in the improvement process and identify their gaps with the smart manufacturing requirements. The papers in De Carolis (2017) establish a roadmap for a unified framework for assessing a manufacturer’s smart manufacturing capability maturity level and identify various technical aspects as critical elements for smart manufacturing assessment[6]. In addition, seven maturity models (MMs) related to smart manufacturing and Industrie 4.0 were selected for contrastive analysis in an article (Gökalp, 2017), and as observed by Gökalp, none of them satisfies all expected criteria. In order to satisfy the need for a structured Industry 4.0 assessment/maturity model, SPICE-based Industry 4.0-MM is proposed in her study[7]. In Schumacher’s research (Schumacher, 2016), not only technical aspects were considered, but also the organizational aspects were included in the assessment[8]. Mittal (2018), among others, from a small and medium-sized enterprises (SMEs) standpoint, revealed that only a limited number of the SM and Industry 4.0 roadmaps, maturity models, frameworks and readiness assessments that are available today reflect the specific requirements and challenges of SMEs[9].

Despite the growing awareness of the smart manufacturing maturity models, few models can faithfully reflect an organization’s maturity level in smart manufacturing as observed. Common sense seems to indicate their importance, but they lack empirical support. In fact, an argument about “productivity paradox” in information technology (IT) field has been continued to this day[10-12]. Brynjolfsson (1993) demonstrated an “alarming correlation” between a sharp drop in productivity and the rapid increase in IT investment in a groundbreaking article. These standpoints empirically support the mismatch between today’s smart manufacturing maturity models and reality.

To date, no clear direction has emerged to suggest how such considerations can be included into smart manufacturing maturity models and assessment practice. In this paper, we present a rough general conceptual framework for understanding smart manufacturing maturity assessment rather than a specific maturity model in order to fill the gaps and revise assessment elements so that the assessment results can truthfully reflect objective facts.

Two questions that need to be answered in this regard are (a) what domains we can identify for smart manufacturing, and (b) how we can harmonize all of the technical and social factors affecting maturity and benefits. It is hoped that answering these questions will contribute to our understanding of the relationships among these factors.

For these objectives to be achieved, the paper is structured as follows. The second section deals with the question (a). After what domains are identified, with the theoretical foundations for the development of the research, and a general conceptual framework for question (b) is then constructed, with a brief synopsis explanation of related prerequisite concepts as a prologue of Section 3. Finally two cases for understanding the results are studied and conclusions are drawn.
2. Smart Manufacturing Domains

2.1. State of the art

How does an enterprise know that they are investing in the right areas to stay competitive? It is significant to point out what areas should be considered when an enterprise embarks on its journey of smart transition. For this purpose, many industrial developed countries have published Smart Manufacturing Reference Models (SMRMs), called national SMRMs in this paper, each with attractive value propositions. A SMRM can clearly reveal what domains should be focused to become a Smart Manufacturing enterprise.

With the publication of various national SMRMs around the world, both the International Electrotechnical Commission Standardization Management Board (IEC/SMB) and International Organization for Standardization Technical Management Board (ISO/TMB) recognized the changing dynamics of manufacturing and the potential opportunities and benefits of developing a reference model for Smart Manufacturing for both the developers and users of standards. So a joint working group named “ISO TC184/IEC TC65 JWG21” was established to create a unified SMRM for smart manufacturing by harmonize existing national SMRMs.

Unfortunately, the international standard for unified SMRM is still in development, and the widely accepted smart manufacturing domains are not yet determined. However, several frequently used dimensions in national SMRMs were identified in JWG21’s technical report[13]. These dimensions from different national SMRMs are listed in table 1.

Table 1. Dimensions from different national SMRMs.

| Model name                  | Dimensions                  |
|-----------------------------|-----------------------------|
| SSIF (SE)                   | Business                    |
| Scandinavian Smart Industry | Product                     |
| Framework                   | Manufacturing               |
| RAMI4.0 (DE)                | Layers                      |
| Reference Architecture      | Life cycle & Value stream   |
| Model Industrie 4.0         | Hierarchy levels            |
| IVRA (JP)                   | Enterprise scope            |
| Industrial Value Chain      | Demand/Supply flow          |
| Reference Architecture      | Knowledge/engineering flow  |
| IMSA (CN)                   | Intelligent function        |
| Intelligent Manufacturing   | Life cycle                  |
| System Framework            | System Hierarchy            |
| NIST model (US)             | Product life cycle          |
| NIST Smart Manufacturing    | Factory life cycle          |
| Standards Landscape        | Order life cycle            |
|                            | Manufacturing pyramid       |

The smart manufacturing domains should be extracted from these dimensions based on an ontological analysis of the activities and processes involved in a manufacturing enterprise. The processes necessary to create a product and to operate a business that manages those processes can be categorised into at least three levels[14] as illustrated in figure 1.

For deriving the smart manufacturing domains, we identify four significant perspectives: Business, Product, Factory, and Operations Management. The dimensions above can be mapped to these four perspectives as table 2.
Activities to create and support the facilities (or means) required to carry out the operational level activities:
• Production system engineering
• Plant/factory construction
• Tools development

Table 2. Mappings from perspectives to dimensions.

| Perspectives            | Dimensions                                                                 |
|-------------------------|-----------------------------------------------------------------------------|
| Business                | Business(SSIF), Layers, Demand/Supply flow, Order life cycle                |
| Product                 | Product(SSIF), Life cycle & Value stream, Knowledge/engineering flow, Life cycle, Product life cycle |
| Factory                 | Hierarchy levels, System Hierarchy, Factory life cycle, Enterprise scope     |
| Operations Management   | Manufacturing, Manufacturing pyramid                                         |

Only one dimension cannot be mapped to any of the four perspectives, which is “Intelligent function” from national model “IMSA (CN)”. Dimension “Intelligent function” also means smart technology, which will be treated as an orthogonal perspective with other four. This is based on an idea that smart technologies are used to improve performance aspects of the activities and processes represented by the four perspectives.

2.2. Identifying Smart Manufacturing Domains
Unlike the perspective “smart technology”, the first three perspectives “Business”, “Product”, and “Factory” converge at the fourth perspective “Operations Management”, rather than orthogonal with each other.

We apply the perspective “smart technology” to the other four perspectives and derive four Smart Manufacturing Domains respectively:
- Applying “smart technology” to “Business” for deriving Smart Manufacturing Domain “connected supply chain”.
- Apply “smart technology” to “Product” for deriving Smart Manufacturing Domain “digital thread”.
- Apply “smart technology” to “Factory” for deriving Smart Manufacturing Domain “smart factory”.
- Apply “smart technology” to “Operations Management” for deriving Smart Manufacturing Domain “digital operations management”[15].

These results are exactly the same as the reference [16]. The relationship among these four domains are illustrated in figure 2. Each of the smart manufacturing domains will be depicted in brief as follows.
2.2.1. Connected supply chain. The expectation of supply chain in smart manufacturing is to create an end-to-end system with real-time information sharing. In this integrated system, each plant is a node in a multi-level value chain, and each of these plant nodes needs to be ready to participate in this new era of real-time digital data exchange.

2.2.2. Digital thread. Although the utilization of CAD/CAE/CAM in product and process engineering is well established and we have learned how to use them to make our works more digitization and easier, it is still common to see that many manufacturers convert digital definition files (such as CAD models) into paper documents (such as drawings and instructions) for execution. So there may be a lot of opportunities for improvement by extending this digital thread.

2.2.3. Smart factory. In terms of data-driven, real-time information sharing and flowing along the supply chain have posed challenges to data transparency within the factory. The flow speed of information in the supply chain will be subject to its flow speed in the factory. For the purpose of internal data transparency and flowing, first of all, it must be achieved that connect as many factory resources as possible using IoT (internet of things), including equipment, people, materials, products, and information systems. Then the data should be gathered directly from equipment as close to real-time as possible, aggregated at different levels, and contextualized for situation understanding and analysis. More data means more insights into improvement opportunities. It is why the IoT becomes a key aspect of smart factory.

2.2.4. Digital operations management. Once the factory resources have active or passive digital communication ability, and become parts of the IoT, abundant smart information is ready for acquisition, contextualization, aggregation, analysis and establishing causal relationship. Future operations management should advance to decentralization to fit data-driven goals[17]. The decentralization of data refers to separating data from the centralized business process that used to be controlled by several information systems. The decentralized data will be aggregated and contextualized according to operations management events rather than based on the traditional E-R model. This means a massive breakdown of existing operations management information systems, such as manufacturing execution system (MES), laboratory information management system (LIMS), etc.
3. Constructing a Maturity Assessment Framework for Smart Manufacturing

Many articles about IT use in organizations published during the past twenty years employ one of the following three terms: “Materiality”, “Sociomateriality”, or “Socio-Technical Systems”[18]. Anaya (2013) provides a discussion about how sociomateriality can enrich the understanding of benefits realization from information systems[19]. According to the theory of socio-technical systems, the technical system alone cannot play role of improving enterprise efficiency and capability maturity. It is necessary to introduce changes to both technology and routines simultaneously, so as to form an interwoven relationship between them, which is called imbrication in sociomateriality theory.

Smart manufacturing is a technology intensive manufacturing paradigm encompassing aforementioned four domains armed with a large amount of smart technologies. So an enterprise initiating smart manufacturing transition shall be treated as a socio-technical system for understanding all the factors that impact the maturity level.

3.1. Related prerequisite concepts

According to Orlikowski (2008), technologies have material properties that can afford different possibilities, giving humans the capacity to act upon and exploit the huge capabilities of these technologies[20]. This characteristic of technologies is termed as “materiality”.

On the other hand, from a viewpoint of relational ontology that presumes the social and the material are inherently inseparable, people and things only exist in relation to each other. In other words, entities, whether humans or technologies, have no inherent properties, but acquire form, attributes, and capabilities through their interconnection with each other[20].

As Leonardi (2012) has pointed: (1) all materiality is interpreted and used in social context and (2) all social action is possible because of some materiality, and the term “sociomateriality” should be used for representing the enactment of a particular set of activities that meld materiality with institutions, norms, discourses, and all other phenomena we typically define as “social” [18].

Orlikowski (2007) has argued in his opinion that what is sociomaterial is not the technology, but the “practice” in which the technology is embedded[21]. To weave the arguments, Leonardi (2012) had made a further suggestion that a new term “sociomaterial practice” should be put forward for representing the space in which human (social) agencies and material agencies are imbricated. This has led directly to the emergence of the modern concept of socio-technical systems. These two agencies can be represented by routines and technologies[22], as illustrated in figure 3.

![Figure 3. From sociomaterial practice to socio-technical system.](image)

Accordingly, the realized benefits from technologies including information systems and physical systems emerge when people interweave with the system in sociomaterial practice. Thus, the benefits from information systems are not inherent in the systems’ material properties, but they emerge from how people experience their agency to change and adapt the systems for their needs. It is also based on how the material agency gives humans the opportunity to find new uses of the system, such as developing new practices or changing the existing routines[19].

As a socio-technical system, the enterprise has some degree of stability because of path dependence which is mainly caused by routines. Cognitive routines may lock human in a specific development direction, lacking of vision and judgement of other development paths, consequently, core
competencies my become core rigidity. It is proposed that enterprises should change their business routines and business processes to realize the benefits from information systems[23].

Using the affordance and constraint lens, in which affordance is the idea that technology makes specific task easier in human’s lives, while constraints make tasks harder to complete[24], it is assumed that people have goals that “the technology made possible, but difficult to achieve, so the exercised their human agency to change their routines so they could still achieve their goals in spite of the constrains they perceived material agency created for them” [19].

3.2. Presuppositions and assertions

Through the above complicated concepts analysis, a set of assertions that serve as the foundation of constructing the maturity assessment framework could be summarized. The first assertion is already implied in the above analysis.

**Assertion 1**: An enterprise initiating smart manufacturing transition shall be conceptualized as a socio-technical system. □

Next, we will reveal the relationship between the smart manufacturing domains and socio-technical system in Assertion 2.

**Assertion 2**: The smart manufacturing domains specify the domains to be assessed for evaluating the maturity level, while the socio-technical system organizes all the maturity assessment factors together, which are divided into two aspects: socio subsystem and technical subsystem. □

Then, the assessment factors embodied in socio subsystem and technical subsystem should be provided in respectively Assertion 3 and Assertion 4.

**Assertion 3**: As far as the scope of this research is concerned, the followings but not limit to norms, policies, institutions, procedures, routines and roles should be taken into account in socio subsystem. □

It should be noted that the words adopted in Assertion 3 for representing assessment factors indicates their common meanings in socio life’s vocabularies.

**Assertion 4**: As far as the scope of this research is concerned, human agencies, cyber artifacts, physical artifacts should be taken into account in technical subsystem, which are corresponding to human, cyber and physical spheres in smart manufacturing definition given by ISO/TMB/SMCC. □

In particular, human agencies have been considered as a factor belonging to technical subsystem in Assertion 4, according to Leonardi (2012), because the conceptualization of a technical subsystem very much resembles what scholars today call sociomaterial practice that encompasses human agencies[18].

Finally, a maturity assessment framework of smart manufacturing can be constructed in Assertion 5 as follows:

**Assertion 5**: A maturity assessment framework of smart manufacturing specifies a space for collections of smart manufacturing capability maturity models, in which, each maturity model can be determined by three facets: smart manufacturing domains, factors, and visions. □

In terms of Assertion 5, other specific smart manufacturing capability maturity models can be obtained by instantiating this maturity assessment framework. The visions of smart manufacturing have been extracted with some modifications from “ISO SAG Industry4.0/SM, Final report to TMB, Clause 2. The vision of smart manufacturing, September 2016” by JWG21[13].

3.3. Maturity assessment framework of smart manufacturing

On the basis of above assertions, the maturity assessment framework of smart manufacturing can be constructed in an illustrated way as shown in figure 4, in which, a roadmap of deduction for our framework from sources by means of assertions is presented clearly.

In order to enhance the expression ability of our maturity assessment framework, the visions on human agencies, cyber artifacts, and physical artifacts should be refined by smart manufacturing characteristics and enriched on the basis of JWG21.

According to Mittal (2017), 27 characteristics identified in literature defining smart manufacturing system were listed and grouped into several clusters[25]. The correspondences between the technical
subsystem aspect and smart manufacturing characteristics are listed in Table 3. These smart manufacturing visions indicate some certain levels that the enterprises expect to achieve in human agencies, cyber artifacts, and physical artifacts through smart manufacturing.

Table 3. Correspondences between the technical subsystem aspect and smart manufacturing characteristics (visions).

| Technical subsystem aspect | Smart manufacturing characteristics (visions) |
|----------------------------|----------------------------------------------|
| Human agencies             | Reliability, Agility, Responsiveness, Accuracy, Resilience, Sustainability |
|                            | Modularity, Scalability, Context awareness, Adaptability, Robustness, | |
| Cyber artifacts            | Interoperability, Networkability, Information appropriateness, | |
|                            | Integrability, Reusability, Composability, Decentralized, Distributed |
| Physical artifacts         | Digital presence, Modularity, Scalability, Context awareness, Autonomy, | |
|                            | Adaptability, Asset self-awareness, Robustness, Flexibility, Integrability, Fully automated, Interoperability, Networkability, Compositionality, Composability, Proactivity, Reusability, Distributed |

4. Case Study and discussions

Let us consider now an example of how the specific capability maturity model can be explained and understood in our assessment framework. A capability maturity model for manufacturing operations management (short for MOM/CMM in this research) had been proposed by Brandl (2016) in his whitepaper [26], in which, three evaluation elements of Policies & Procedures, People, and Tools had been comprehensively considered (as listed in Table 4).

The relationships among these elements are illustrated in Figure 5, in which, the coloured ellipses indicates the evaluation elements mentioned in MOM/CMM. People and Tools are mutually shaped under the constraints of Norms (not included in MOM/CMM), Policies, and Procedures. The resulting activities are so-called sociomaterial practice as has been discussed. Human agencies are regarded as the aggregation of people’s roles, responsibilities, and skills obtained by training. This abstract concept indicates the capacity to perform these activities.

MOM/CMM took the factors both in socio aspect and technical aspect into account and focused on the manufacturing operations management domain, but it is slightly distinct from the digital operations
management domain, because it did not emphasize the application of smart technologies in MOM. The generation of MOM/CMM from the assessment framework can be illustrated in figure 6.

Table 4. Three evaluation elements from [26].

| Evaluation elements (visions) | Descriptions |
|------------------------------|--------------|
| Policies & Procedures (documented) | - Corresponding to policies and procedures in socio aspect.  
- A policy is a high-level overall plan embracing the general goals and acceptable procedures, especially of a governmental body [26].  
- A procedure is a series of actions done in a certain sequence or order that establish an accepted way of implementing a policy [26].  
- The requirement to Policies & Procedures is formally written and controlled documented. |
| People (Reliability) | - Corresponding to human agencies in technical aspect.  
- People implement policies and follow procedures [26].  
- The requirement to People is well trained in policies, procedures, and tools |
| Tools (Flexibility/Integrability) | - Corresponding to cyber artifacts in technical aspect.  
- Tools support, formalize and implement procedures [26].  
- The requirement to software tools is information integration and lifecycle management, such as regular updating, obsoleting and replacement. |

Figure 5. Relationships among the evaluation elements in MOM/CMM.

Figure 6. Generation of MOM/CMM from assessment framework.

5. Conclusions

In this paper, we present a rough assessment framework for smart manufacturing and how to understand specific maturity models within the framework. We will begin our conclusions by reviewing the research questions, and then turn to the summaries of our findings.

We first posed two questions of (a) what domains we can identify for smart manufacturing, and (b) how we can harmonize all of the technical and social factors affecting maturity and benefits to be replied to for purpose of constructing a smart manufacturing maturity assessment framework. Secondly, some possible smart manufacturing domains were suggested on the basis of literature review and analysis, but they were not the unique or only acceptable results. Thirdly, a maturity assessment framework was attempted to derive from the socio-technical perspective in an analytical way.
The study in this paper is theoretical rather than empirical because the findings are built on conceptual analysis, not data or observations. In general, this inductive assessment framework is metaphysical and abstract, and may be regarded as a meta-model or reference model for specific maturity models. These findings are in line with previous studies on smart manufacturing maturity models, although no previous study has asked this question in detail.

These findings lead us to believe that the factors of socio aspect directly affect the maturity level of smart manufacturing, while the factors of technical aspect indirectly keep the enterprises at a high level of maturity. More comprehensive maturity models considering both socio aspect and technical aspect should be developed for smart manufacturing assessment within the framework proposed by this research.

Even though this body of research has the merit of offering valuable insights into the maturity assessment, it has some limitations, for example, the identification of smart manufacturing domains is a controversial issue, and using this framework to actually conduct the assessment work is still open to question. Future work will hopefully clarify this important implementation concern. More research is needed on questionnaire design for implementing the functions of the assessment framework.

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