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Methodology for Aligning Factory Information and Control Systems in a Complex and Dynamic Environment: Case of Semiconductor Manufacturing

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Abstract: Business and information system alignment is key to improve business performance. Yet, little studies show practically how to achieve an efficient fit between business and IT. This paper proposes a methodology for accompanying the evolution of factory information and control systems for complex enterprises in an agile environment, from a functional standpoint. The methodology relies on capturing user requirements in a Reference Model and finding acceptable compromises of IT development, to reach the alignment incrementally. The methodology has been designed at 300mm unit of STMicroelectronics in Crolles. It is currently under deployment.

Keywords: Business / IT Alignment, Factory Information and Control Systems, Enterprise Architecture, Semiconductor Manufacturing

1. INTRODUCTION

The role of Information Systems (IS) is critical in supporting complex organizational processes. This role is even more critical when companies operate in an uncertain and extremely competitive environment. This situation is particularly striking in the electronics industry because of the complexity of the production environment (Mönch et al., 2011; Chien et al., 2011), and the strong interactions between its various technical domains. Adaptability is vital to semiconductor manufacturers, so that they can minimize the time to market and constantly provide customers with leading edge products. The highly automated production processes have to be flexible and agile. This requires a robust Factory Information and Control System (FICS) able to fulfill its missions and ensure business continuity by frequently integrating new changes. The necessity of Business / Information Technology (IT) alignment is a key to competitiveness to ensure the best possible performance in semiconductor manufacturing . One of the major challenges facing manufacturing organization is then to be able to anticipate the evolution of business processes in order to integrate corresponding FICS solutions in line with new business needs.

In this article, we focus on the functional aspect of the evolution of FICS. Our research efforts are consistent with previous work in the field of semiconductor manufacturing. (Chapron et al., 2008; Boucher et al., 2011) have initiated the analysis of evolution issues in complex organizations, considering the semiconductor manufacturing case. They present an innovative formalization of dependencies between enterprise processes; this formalization helps to improve the management of the transformation of IS.

In this paper, we propose a methodology within Enterprise Architecture (EA) to facilitate the evolution of FICS in complex and dynamic environments. Our approach is centered on user requirements expressed without any reference to an existing system and any technical/cost constraints or limitations. Once captured, these requirements constitute a model which, used as a reference, helps to dissociate the expression of emergent needs from the technical solutions to be implemented.

The paper is organized as follows. Section 2 describes the context of application of the proposed methodology. Section 3 discusses EA and alignment issues. Section 4 presents the new methodology. Its relevance is discussed in Section 5. Finally, in Section 6, we draw conclusions and outline some important perspectives.

2. CONTEXT: SEMICONDUCTOR MANUFACTURING

The methodology proposed in this paper has been elaborated to answer the needs of the 300mm production unit of STMicroelectronics in Crolles. Though not tested elsewhere, we are convinced that the approach could be valuable for any other semiconductor manufacturing facility. Moreover, we strongly believe that it could be extended to other industries sharing the same key characteristics than the production of electronic components, i.e. (i) high complexity of the manufacturing processes, (ii) significant pace of change in the internal or external configuration of the processes, and (iii) highly automated processes where information technology plays a critical role.

Among the major industries, semiconductor manufacturing is with no doubt the fastest evolving one (Moyne et al., 2010). It is driven by an increasing demand for integrated circuits in almost every domain of our life (automotive, communication, entertainment, health care, energy saving, etc.). Already in 2010, it was estimated that, on average, a person was using more than 250 chips and 1 billion transistors per day! The ever evolving offer of products and services, the race for more autonomy, less consumption and more computation power at lower price are the driving forces that shape the semiconductor industry.

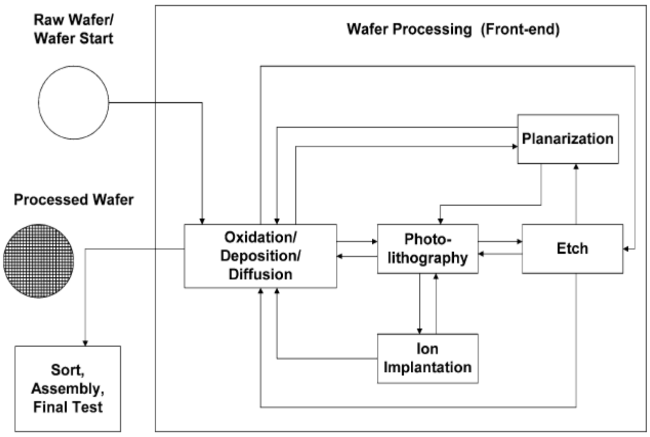

Fig. 1. Main work area in wafer fab (Mönch et al., 2011)

The manufacturing of semiconductor components is done in two main steps usually called “front-end” and “back-end”. In front-end, components are “printed” on silicon wafers which are then sawn in dices or “chips” and encapsulated in back-end. Our case study is in a front-end facility where producing a wafer requires more than 300 individual operations. Each of these operations is operated on various production tools, and each operation is itself composed of several steps in the various modules of the tool. The fabrication basically consists of stacking and etching various layers and patterns on the silicon, to get the final circuit as illustrated in Fig. 1.

As with the reduction of device size, equipment is becoming very expensive (an up-to-date production plant is typically worth several billions of dollars), the same machines are used several times in the flow and for several generations of products. Moreover, in order to maximize the return on investment, the fabrication line has to be used at maximum capacity, all over the range of technologies it must produce. In a typical “high mix” fab, it is usual to run in parallel more than 500 different products ranging from 10 years-old technology to brand new ones.

As geometries shrink toward 14nm and below, new process constraints appear every day claiming for new mechanisms, methods and tools to master them. Manufacturing automation is then mandatory to cope with process complexity (same tools used on different products, at different stages with specific set-up and constraints).

FICS are paramount and must follow the pace of changes of the manufacturing processes. However, due to the (short) history of the industry, solutions have very often been built as stand-alone, isolated and (heavily) customized applications. FICS are then difficult to extend to support new needs (Da-Yin, 2010). To balance technical and delay constraints, a trade-off is often made by lessening user requirements in order to be able to deliver a solution faster. This will in turn subsequently shape the expression of user needs and push users to think in terms of limited evolutions of existing application, rather than in terms of actual business needs. With time, this will blur business needs and severely lower the overall performance of the organization.

The example of processability developed in (Ben Amira et al., 2013) highlights the difficulty to properly identify existing constraints and to adapt FICS to take new items into account. Processability is a function which is specific to semiconductor manufacturing and does not exist in most other industries where only the maintenance status of tools is considered; see (Ben Amira et al., 2013) for more details. The challenge to face in the 300mm unit of STMicroelectronics in Crolles is to be able to support the deployment of new technology nodes by permanently aligning FICS on ever evolving requirements or, in other words, to manage a rate of requirements which is greater than the time needed to deliver FICS solutions.

3. ENTERPRISE ARCHITECTURE AND ALIGNMENT

3.1 Articulation between Enterprise Architecture and Alignment

The challenge of “fitting” IT solutions to business requirements is not new (Silvius, 2009). The concept of alignment business / IT comes from the one of strategic alignment, which was developed more than two decades ago. The growing role of IT in organizations imposes the alignment of their use with business processes and strategy. In response, several methodologies have been developed as for example Business Systems Planning and Business Information Control Study; see (Zachman, 1982) for more details. These methodologies can be considered as early appearances of IT alignment (Chan et al., 2007). (Henderson and Venkatraman, 1993) proposed a framework known as the Strategic Alignment Model (SAM), which is the most widely cited, widespread and accepted framework of alignment (Chan et al., 2007; Wan et al., 2008). The SAM aims at establishing consistency between (i) the external domain of business strategy and IT strategy; and (ii) the internal domain focusing on organizational infrastructure and processes, and IT infrastructure and process. This model (Fig. 2) describes the relations between external and internal environments of the same domain, and between business and IT domains (Avila et al., 2009).

However, using SAM to deal with alignment issues is still limited in theory and practice, EA comes out to take this responsibility (Wang et al., 2008). EA is considered as a key “tool” to support enterprise engineering by helping stakeholders to manage changes at all levels: Strategic, organizational, and IT issues (Chen et al., 2008b; Lankhorst, 2009). In addition to present a coherent explanation of the what, why and how of a business, EA aims at supporting business analysis like alignment between business functions and IT systems (Pereira and Sousa, 2005; Wang et al., 2008), or change management from current state “As is” to desired state “To be”. One of the main goals of EA managing is to establish and continuously maintain alignment between business and IT aspects (Abraham et al., 2012; Radeke, 2011).

In the following, we present the limitations of existing alignment methodologies, in particular EA, in the context of semiconductor manufacturing.

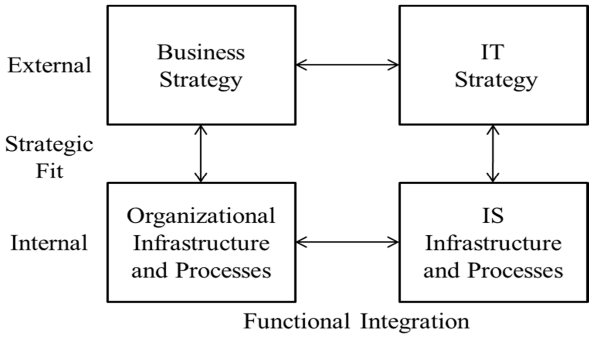

Fig. 2. Strategic Alignment Model (Henderson and Venkatraman, 1993)

3.2 Limitations of Current Methodologies to Achieve Business / IT Alignment in Semiconductor Manufacturing

We consider the following definition of EA: "a coherent whole of principles, methods, and models that are used in the design and realisation of an enterprise's organisational structure, business processes, information systems, and infrastructure" (Lankhorst, 2009). To deal with alignment issues, EA enables to pinpoint (Sessions 2007):

- System complexity: Causing an increase in expenditures for building IT systems.
- Poor business alignment: Organizations are finding more and more difficult to keep those increasingly expensive IT systems aligned with business needs.

Semiconductor manufacturing has to be agile and changes can hardly be anticipated or planned. In this context, the approaches analyzed in (Avila et al., 2009) and based on paths linking organizational and IT infrastructures and processes are hardly applicable because they were designed for an environment where changes are planned and not repetitive. The next limitation of alignment approaches for semiconductor manufacturing, considering the analysis in (Avila et al., 2009), is that they implicitly assume that the IT evolution cycle is shorter than the one of business practices. This is quite the opposite in the context of our study and impacts the way we interpret the temporal dimension. As argued in Section 2, the current state "As is" reflects a trade-off between the vision of the users and IT as a result of the evolution of a previous state. The quality of user requirements is impacted by the time constraint imposed by the delays needed to implement solutions, thus strengthening the vicious circle, whereas special attention should be given to understand business and its articulation with IT.

At another level, the repetitive nature of alignment in semiconductor manufacturing limits the approaches that could be applied to only the SEAM (Systemic Enterprise Architecture Methodology) (Avila et al., 2009). The SEAM is a hierarchy of systems that span from business down to IT. It is based on an iterative method to describe future states for each level by taking into account the possible changes that could take place (Wegmann et al., 2007). However, in semiconductor manufacturing, changes are emergent and difficult to plan: Changes are most of the time reactive instead of being proactive. Moreover, the scenarios proposed for changes are divergent and provide a wide range of possibilities. Thus, the SEAM approach seems to be inadequate. In addition, most of Business and IT alignment research focuses on "what" issues (and what to deal with) (Kaidalova and Seigerroth, 2012; Chan et al., 2007), and neglects "how" to conduct and achieve operationally the Business / IT alignment (Kaidalova and Seigerroth, 2012; Silvius et al., 2009). Yet we would point out that EA captures the essentials of the business, IT and its evolution (Jonkers et al., 2006) and defines how information and technology support the business operations: EA could be considered as an efficient methodology to ensure alignment (Pereira and Sousa, 2005; Wang et al., 2008). In line with this, our proposition supports the description, the formalization, and the articulation between the needs of "business processes" layer and the "IT" layer (from a functional point of view) in a coherent way.

However, it must be acknowledged that EA capability to handle models of the whole enterprise at varying degrees of maturity is a particularly delicate task. (Kaisler et al., 2005) focus on limitations of EA summarized in the critical problems of modelling, managing, and maintaining the EA models (business view, functional view, IT view, etc.) for the following reasons: (i) The necessity of different types of modelling expertise to cover all organization facets, (ii) a significant effort required to harmonize heterogeneous models, (iii), an unduly cumbersome procedure for maintaining synchronized models, and (iv) the risk of a wrong interpretation of models that have not all reached the same level of maturity. Indeed, the high complexity of the manufacturing processes and the significant pace of change as detailed in Section 2 make these limitations even more acute. Furthermore, most EA evolve from existing architectures which create tension between the continuing operations and the introduction of enhanced or new systems (Kaisler et al., 2005).

To remedy to these limitations, we propose to create a reference model (than can be seen as a buffer) to take into account both the requirements and their evolutions. This reference model has to be seen as the target to reach by FICS. The methodology to build and use this model is developed in the next section.

4. METHODOLOGY PROPOSED TO FACILITATE THE EVOLUTION OF INFORMATION SYSTEM IN SEMICONDUCTOR MANUFACTURING

In our view, an accurate and detailed functional description of user needs can clarify the evolution path of FICS. From an alignment point of view, if the functional growing and/or changing of user needs is identified and referenced, it is possible to plan the changes of FICS. The challenges are to deal with unanticipated and complex changes, in an environment that is constantly evolving. To meet these challenges, we propose a methodology summarized below.

- Construction of the reference model (detailed in Section 4.1). Special attention is paid to effectively capture user needs and requirements, but also their potential evolution. This functional view is translated in a reference model. The reference model is made up of: (i) the matrix of user requirements (Table 1) which is built without considering FICS constraints in order to guarantee the capture of emergent needs, and (ii) a data model reflecting the matrix of user requirements.

As these needs evolve faster than FICS capability to deliver solutions, the reference model serves as a buffer which has to be used as a driving direction for IT developments, as shown in Figure 3. The reference model has then to be constantly updated with respect to both the evolution of FICS and functional needs.

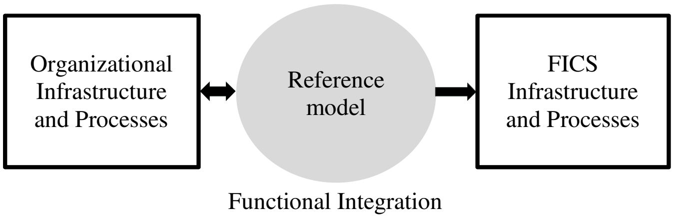

Fig. 3: Business / FICS alignment with reference model

- Rational use of the reference model (detailed in Section 4.2). As technical and cost constraints, hence the imperative to ensure continuity of service, require incremental approach for updating FICS, the reference model has to be seen as the target to achieve. Even if Business / FICS alignment is not achieved in the first iterations, the reference model still represents a clear vision of the desired state to reach.

4.1 Construction of the Reference Model

The first activity deals with elicitation of business requirements stemming from business managers, as well as from operational stakeholders. We struggled to identify the "real" user needs without taking into account the existing system or technical considerations. Therefore, for speed and simplicity reasons, we created a matrix to synthesize the Use Cases (UC) and to identify the corresponding Functional Concepts (FC) that support requirements as illustrated in Table 1.

Table 1. Synthesizing user requirements

Actor	Use Case	FC_1	FC_2	…	FC_i	…	FC_n
a_1, a_3	UC_1		X				X
a_1	UC_2	X	X				
…	…						
a_p	UC_j	X		X			
	…						
a_k	UC_m		X		X		

The advantage of this approach is that it creates a direct link between the use case and the functional view. For example, UC_1 is supported by FC_2 and FC_n, and FC_1 supports UC_2 and UC_j. In addition, this approach summarizes all the use cases covered by each functional concept. For each new requirement, we check if it is not already covered by the current use cases or addressed by an already defined functional concept. We limit ourselves in this study to the static description of requirements; the scope is to provide the functional elements for change. Dynamic aspects will be considered for IT developments. Also, limiting to a structural view helps to communicate with end users.

The functional concepts are the essence of the data model of the reference model (Fig. 3). We define UML class diagrams for each functional concept using following two rules:

- Always use the same modelling choice for similar problems even though different choices may exist. Also, different types of problems should not be addressed by the same modelling solution. To make sure that two equivalent problems are using the same modelling choice, we check the corresponding FC in the matrix of user requirements. Then we apply the same modelling based on the previous version of the reference model if it exists, otherwise we create a new model that will be the reference for all other similar problems in the future. The aim here is to achieve complete consistency of modelling choices and to reduce complexity. This also facilitates the management of a lighter reference model.
- Select the modelling option that ensures the maximum flexibility, i.e. which provides the maximum margin of configurability. Although this rule is conceptual, we should find the right balance between the definition of a specific model for each particular situation, and a generic model meeting the user requirements. Similarly, in order to ensure agility, these choices should not prohibit future evolutions of the model. This also means that, when dealing with a given case study, it is important to extend the reasoning to closely related problems. Let us note that the "modelling team" (Business and IT analysts) defines in a qualitative way the flexibility and agility measurements.

We consider the resulting class diagram as the reference model that captures user requirements. The model is both an accurate picture of the current functional needs, and also a "To be" scenario for FICS. We emphasize that the reference model is not an "As is" picture on the technical / system side, but an "As is" on the functional side. Note that more than one related field of business requirements (maintenance, manufacturing, process control, etc.) may simultaneously evolve. That is where the reference model comes to support an integrated vision of businesses, and enables to pool resources for developing IT solutions.

As shown in Figure 3, the reference model is positioned on the boundary between business and FICS. All business changes are reflected in the reference model and its update must be rapid to ensure its coherency with the evolution of business requirements. The reference model provides functional guarantees for the ability to respond to the dynamic changes of businesses; the function is illustrated by the double arrow between the reference model and the business domain (Fig. 3). For FICS, the reference model is a target to reach, hence the one-way arrow to FICS.

One of the main challenges in constructing the reference model is to properly identify and capture actual user needs and requirements. During our study, we observed that users tend to express their needs by referring to the actual solution they have on hand. Most users are more comfortable to set "functional" expectations regarding existing FICS tools. This does not ensure the proper collection of functional needs and the situation is even worst in a full automation context, because users are overflowed by FICS applications and find themselves "formatted". On top of it, given the rapidly evolving environment in semiconductor manufacturing, constraints as cost or delay of implementation become gradually stronger and so users tend to think in terms of incremental evolution. As a result, the boundaries between business requirements and FICS tools are very often blurred leading to the alignment of business needs to FICS solutions and eventually to condition business evolution to the availability of IT options. Therefore, particular attention should be paid to the elicitation of requirements; see (Aurum and Wohlin, 2005) for a state of art of techniques and approaches for requirement elicitation.

4.1 Rational Use of the Reference Model

The reference model is the cornerstone to support the evolution of both the functional requirements and FICS (Fig. 4):

- From a functional standpoint, all emerging requirements have to be integrated in the reference model considering its previous version. In this way, we ensure a functional continuity of the requirement and, more importantly, we guarantee that the newly expressed requirements are constructed on the basis of the previous functional situation and not on the basis of an existing IT application.
- From an implementation / technical standpoint, the reference model is the target for FICS, hence the importance of synchronizing the model with emergent requirements. Constraints such as costs, delays of implementation and business continuity impose an incremental approach to satisfy the reference model. Given that the evolution of business needs is faster than the time required to implement IT solutions, misalignment and de-synchronization can be noted. Acting as a buffer, the reference model limits the impacts of misalignment because it traces the evolution of user requirements regardless of the availability of FICS solutions. Thus, we can tolerate to miss an updating stage of FICS (to the constraints described in Section 2) provided that efforts are made to reduce the gap in the next iterations.

Figure 4 illustrates the synchronization of user requirements with the versions of the reference model. These versions are built considering emergent user requirements and the current version of the model.

For example, user requirements at time t2 are immediately translated in reference $model_{t2}$ while updating the reference model since t1. Considering IT developments, Business / FCIS alignment is achieved through incremental implementations that can be made at frequencies that are decoupled from the reference model updates.

For example, three Versions (V_0, V_1, and V_2) of the factory information and control system $FICS_{t1}$ at t1 correspond to the some requirement translated in the reference $model_{t1}$. At time t2, new requirements are defined for the reference model but no FICS solutions are delivered due to constraints. For the next update of the FICS, the reference model will be considered taking into account its version at t2. The delay for FICS could be caught up at t3. At t3, the FICS to deliver should reach the reference $model_{t3}$.

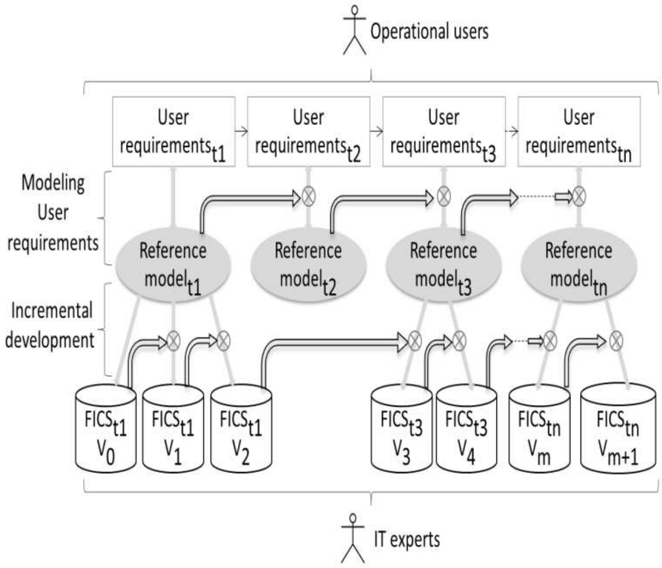

Fig. 4. Using the reference model

From a FICS standpoint, the main challenge in the use of the reference model consists in mastering the trade-off between development cost and delay and the gap with business needs (alignment). Last, but not least, part of the challenge also lays in the way the IT team adheres to the methodology!

5. DISCUSSION

Complex organizations which evolve in a dynamic and rapidly changing environment need to constantly adapt their FICS to emerging business needs. From a functional standpoint, repetitive cycles of evolution may adversely affect the proper elicitation of requirements. The approach proposed in this paper aims at capturing the exact requirements and at facilitating change management; the method offers a practical means to achieve a better alignment between FICS and business needs. We consider that the proposed reference model is an efficient tool to support the functional view of EA, setting a functional path for FICS evolution. The main benefits can be summarized as follows.

- For business: Giving a whole picture of the interactions between functional domains or items and modelling user requirements together with their evolution.
- For IT: Supporting discussions and helping decisions between business stakeholders and IT experts when a trade-off has to be made for the evolution of FICS, and pooling the IT development resources.

The proposed approach has been initiated at the 300mm production unit of STMicroelectronics in Crolles for processability (Ben Amira et al., 2013). The first step was to capture user requirements and then to define use cases as well as the corresponding functional concept. Each functional concept was defined as an answer to a processability requirement. The reference model was elaborated considering those items and taking into account other manufacturing elements such as maintenance, process control, etc. It is currently used as a medium to validate processability requirements between field users and the IT Team on one hand, and to set trade-offs for the update of FICS on the other hand. By adopting the proposed methodology, the elicitation of sound user requirement was simplified, hence their gradual integration in FICS.

6. CONCLUSION AND PERSPECTIVES

In modern businesses and organizations, keeping pace with user requirements and the constantly evolving environment is a critical key to prosperity. Two core imperatives are essential: (i) The ability to capture user requirements, and (ii) the capability to efficiently translate these requirements to FICS. This paper presented a new methodology to Business / IT problem considering a functional point of view. It could be seen as a support for EA functional analysis to achieve Business / IT alignment. The proposed methodology aims at taking into account the limitations of current alignment approaches. The methodology will be illustrated in more details on the processability use case in a follow-up paper.

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