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Mapping Strategic Goals and Operational Performance Metrics for Smart Manufacturing Systems

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Abstract

The complexity of the relationship of strategic goals to operational performance across the many levels of a manufacturing system inhibits the realization of Smart Manufacturing Systems (SMS). This paper proposes a method for identifying what aspects of a manufacturing system should be addressed to respond to changing strategic goals. The method uses standard techniques in specifying a manufacturing system and the relationship between strategic goals and operational performance metrics. Two existing reference models related to manufacturing operations are represented formally and integrated to support the proposed method. The method is illustrated for a single scenario using agility as a strategic goal. By replicating the proposed method for other strategic goals and with multiple scenarios, a comprehensive set of performance challenges can be identified.

Keywords: Smart Manufacturing System; formal methods; agility; SCOR; SIMA; OWL; IDEF0

1. Introduction

Smart Manufacturing Systems (SMS) are defined by the advent of new technologies that promote rapid and widespread information flow within the systems and surrounding its control. Along with these technologies, however, comes a greater need to be able to respond to information quickly and effectively, thereby disrupting ongoing processes. SMS agilely adapt to new situations by using real-time data for intelligent decision-making, as well as

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predicting and preventing failures proactively. To support this agility SMS need to meet rigorous performance requirements where performance measures accurately and effectively establish targets, assure conformance to these targets, and flag performance issues as evidenced by deviations from performance expectations (Davis et al. 2012). By putting in place a continuous performance assurance process, companies can ensure products are manufactured through manufacturing processes.

Both new and longstanding challenges at all levels of a manufacturing system inhibit the realization of SMS. This paper makes a contribution by proposing a challenges-identification method that enables focusing on a particular aspect of a manufacturing system to scope the challenges. The proposed method maps two existing models related to manufacturing operations: the Supply Chain Operations Reference (SCOR) from the Supply Chain Council (SCC. 2012), and the manufacturing activity models from the SIMA (Systems Integration for Manufacturing Applications) Reference Architecture (Barkmeyer. 1996)

The SCOR model defines a system for organizing performance metrics and for associating those metrics with strategic goals and business processes. The SIMA Reference Architecture defines a set of activities describing the operational aspects of manufacturing a product from conception through production. The two models overlap where the business processes from SCOR directly correspond with the more extensive SIMA operational activities. Our goal in integrating these two models is to illustrate how performance metrics from the business-focused SCOR model can be identified for the operational activities of the SIMA model. We base this mapping on the use of formal representation methods for defining both models.

Figure 1 depicts how performance metrics are identified in the SCOR model. In this example, the agility goal is selected from the SCOR model. The agility goal is defined as the percentage of orders which are perfectly fulfilled when a disturbance is introduced into the manufacturing system. The disturbance in this case is a sudden increase in customer demand (McDaniels et al. 2008).

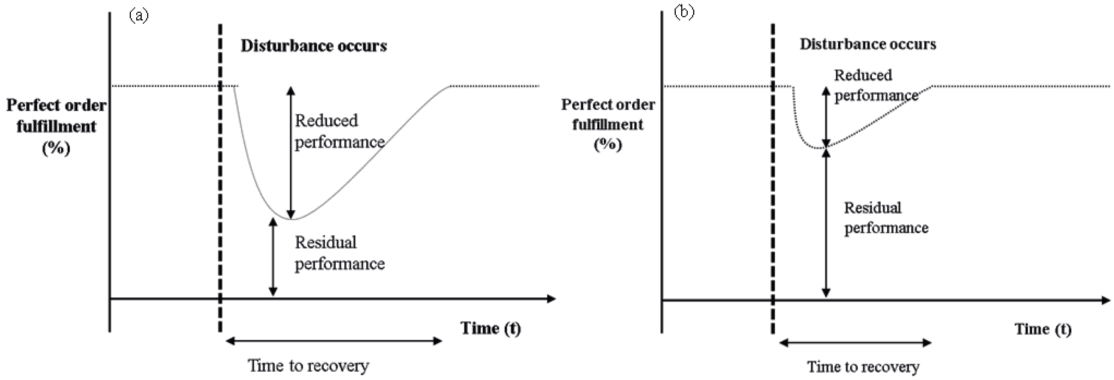

Fig 1: Illustrative manufacturing system performance (a) Current manufacturing system; (b) Planned manufacturing system

The agility is a function of time to recovery and residual performance: Agility=f(time to recovery, residual performance). Agility enables the manufacturing system to shorten the time to recovery while also maintaining a high level of residual performance during the disturbance. Parts a and b in the figure illustrate a measurable improvement in agility between an existing system and a planned system. The challenge to improving agility is then reduced to challenges in improving these two performance metrics. While the goal of agility is not measured directly, performance metrics which are measurable are used to measure the capability of the manufacturing system to achieve the agility goal. In this paper, we explain how the proposed method can be consistently implemented for various goals and performance metrics using the formal representation methods for the two foundation models.

The remainder of this paper is organized as follows. Section 2 provides background on the representation methods. We describe the challenges-identification method in Section 3, illustrate it with an example, and show how it can be used to identify challenges for performance assurance. Finally, we present our conclusion and future work.

2. Background

In this section, we review the use of two formal representation methods used in the proposed challenges-identification method. For the SCOR model we develop an ontology using the Web Ontology Language (OWL) (W3C Recommendation. 2012) The SIMA activity models are represented in IDEF0 (FIPS183. 1993, Colquhoun, Ray, and Roger. 1993.) OWL is a knowledge representation language for authoring ontologies. It is based on description logic, which is a subset of first order logic. Gruber defines an ontology as the specification of conceptualization in formal description (Gruber. 1993). An ontology is a set of definitions of classes, properties and rules describing the way those classes and properties are employed.

We use OWL to formally represent the major concepts and relationships described in SCOR. SCOR lends itself to representation in OWL in that it contains a rich network of definitions hierarchical which are interconnected with each other. Each of these abstract concepts is decomposed hierarchically in the SCOR model, and different elements across the decompositions are associated to each other. For example, SCOR contains a model of the business activities associated with all phases of satisfying a customer's demand. The model consists of the four major components: performance, processes, practices and people. For the purpose of identifying challenges to SMS, only the performance and process components depicted in Figure 2 are used in the examples. Ovals represent the classes. Arrows refer to object properties.

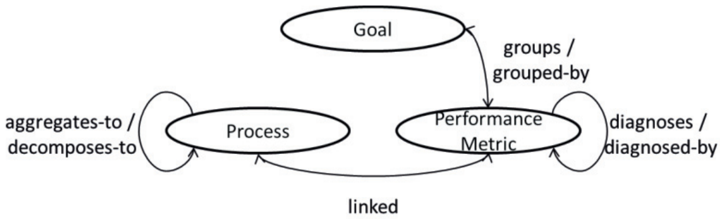

Fig 2: Major SCOR ontology concepts, relationships and properties

The performance component of SCOR provides metrics to describe process performance and define strategic goals. The process component provides standard descriptions of management or business processes and process relationships. Additionally, SCOR contains a hierarchical model of performance metrics and their association with strategic goals (called *Performance Attributes*.) The mappings between performance metrics and processes make explicit the identification of processes relevant to specific performance metrics, and vice versa. The ontology provides a formality for SCOR which enables reusability. In addition, a query language known as DL Query (W3C Recommendation. 2012) that is available so that we may create and reuse queries on the model.

IDEF0 models consist of a hierarchy of interlinked diagrams with defined terms. The diagrams present activities as boxes. Arrows attached to the boxes indicate the interfaces between activities. The interfaces can be one of four types: input, control, output or mechanism. An IDEF0 model represents the entire system as a single activity at the highest level. This activity diagram is broken down into more detailed diagrams until the necessary detail is presented for the specified purpose. The SIMA activity model is used to reference and represent a manufacturing system. It describes the principal technical activities involved in the engineering and production activities of a manufacturing enterprise. The model describes the top level activities and information flows shared in a typical manufacturing enterprise. Note that what is referred to as activities in IDEF0 are very similar to the processes in the SCOR model. The ontology facilitates this semantic mapping.

Figure 3 depicts the activity A413 Create Production Orders, one of the lower level activities from the SIMA model. The arrows entering the activity from the left represent processing inputs to the activity, in this case the Master Production Schedule. The arrows coming in from above represent controls that guide the activity. For example, Planning Policies for a given organization will guide the creation of production orders. Arrows on the right are outputs from the activity, in this case tooling, material, and production orders. Finally, arrows coming in from the bottom represent controls on the activity. Collectively these arrows are referred to as ICOMs in IDEF. Colored arrows represent the additional elements required by the planned manufacturing system. Figure 4 depicts the next level of break down for this activity as is indicated by the numbers labeled on each box which all begin with A413.

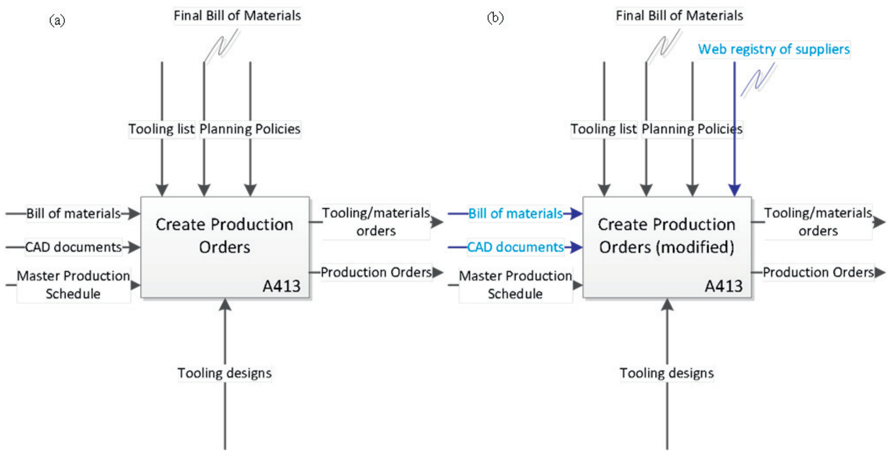

Fig 3: Activity of interest

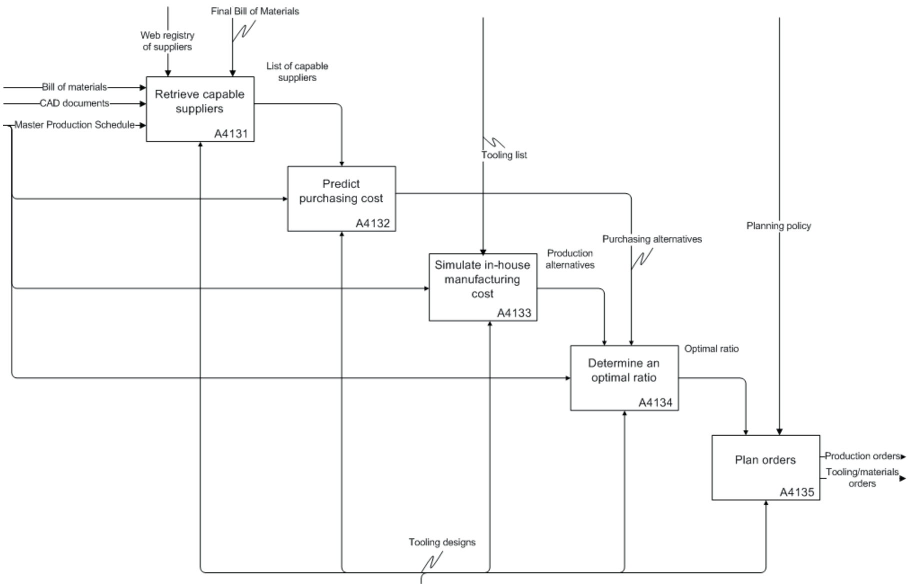

Fig 4: A413 activity model modified (decomposed)

3. Challenges in mapping strategic goals and operational performance metrics

One of the drivers for smart manufacturing is the need to respond to changes in demand more quickly and efficiently. To illustrate this scenario we consider how a manufacturing operation might respond to an order it is not able to fulfil in its entirety in-house in the time frame needed. In this case, we postulate that the manufacturer could fill the order by outsourcing a portion of the production needs through the use of smart manufacturing technologies that would enable them to identify suitable and capable partners. The understanding of how to implement such a scenario down to the operational level is one of the grand challenges in modelling of complex manufacturing systems (Fowler and Rose. 2004) and is the objective of our challenges-identification method. An order of scope reduction is needed for any requirements analysis to be meaningful and practical. Using the formal methods described we are able to precisely delineate scope. Table 1 shows the proposed challenges-identification method that integrates SCOR, SIMA Reference Architecture, and scenario-based validation.

Table 1: The proposed challenges-identification method

Scope determination	Identifies performance metrics of a manufacturing system using SCOR
Current manufacturing system representation	Identifies activities related to the performance metrics using IDEF0
Planned manufacturing system representation	Creates an activity model for the planned manufacturing system activity model by modifying the current
Gap analysis	Compares the activity models of the current and the planned systems to identify the challenges and associated metrics

To determine a scope, we use the SCOR mappings between performance goals and performance metrics of a manufacturing system. Further, SCOR links the performance metrics to business processes which can be aligned to activities in a manufacturing system. These mappings determine the scope by identifying the relevant activities. The activities are drawn from the SIMA models which represented the *current manufacturing system*. We then create a *planned manufacturing system* activity model to identify additional capabilities. The planned activities reflect the enhanced capabilities envisioned for smart manufacturing and are then validated through a realistic scenario. Through a realistic scenario, a gap analysis between the activity model of the current and that of planned system identifies challenges in the specific terms associated with the IDEF ICOMs. Table 1 summarizes these steps and they are illustrated below in the context of an example based on the *Create Production Order* activity.

3.1. Scope determination

To evaluate performance with respect to SMS goals, we identify specific business processes that contribute to a goal and subsequently the activities which support those processes. The SMS concept has several goals including agility, productivity, sustainability (NIST, 2014) and others (Hon. 2005). In this paper, agility is selected to test the proposed challenges-identification method. In the SCOR ontology agility is a strategic goal. Goals are related to performance metrics as is shown in Figure 2. Figure 5a shows the results of querying the ontology to find the performance metrics related to the agility goal. Performance metrics are organized hierarchically. Figure 5b shows

Query (class expression)	Performance_Metric and (grouped-by value Agility)
Query results	Upside_Supply_Chain_Adaptability, Upside_Supply_Chain_Flexibility, Overall_Value-At_Risk, Downside_Supply_Chain_Adaptability

(a) A query to retrieve agility related performance metrics

Upside_Supply_Chain_Flexibility	Individual: Upside_Supply_Chain_Flexibility Types: Level-1_Metric (diagnosed-by Upside_Make_Flexibility) and (diagnosed-by Upside_Source_Return_Flexibility) and (diagnosed-by Upside_Deliver_Flexibility) and (diagnosed-by Upside_Source_Flexibility) and (diagnosed-by Upside_Deliver_Return_Flexibility) and (grouped-by Agility)
Upside_Make-Flexibility	Individual: Upside_Make_Flexibility Types: Level-2_Metric (linked-to Engineer-to-Order) and (linked-to Make-to-Stock) and (linked-to Make-to-Order) and (linked-to Make) and (diagnoses Upside_Supply_Chain_Flexibility) and (grouped-by Agility)

(b) A formal definition for the retrieved performance metrics

Fig 5: Querying and retrieving performance metrics on Protégé 4.3

how one can drill down into lower levels of the hierarchy for one of the agility performance metrics, *Upside_Supply_Chain_Flexibility*, to find the lower level metrics associated with the agility goal and to find processes associated with those metrics. In this case, we find the lower level metric *Upside_Make-Flexibility*.

If one chooses to investigate a performance metric at high level, the subsequent analysis and the identified challenges will likewise be at high level. We identify generic processes that are important to agility: *Engineer-to-Order*, *Make-to-Order* and *Make-to-Stock*. These identified processes are all associated with the process *Schedule production activities* as is shown in Figure 6. *Schedule production activities* can be mapped directly into the *Create Production Orders* activity in the SIMA model. The result of this series of queries and mappings defines the scope for our analysis. This mapping result is summarized in the Table 2.

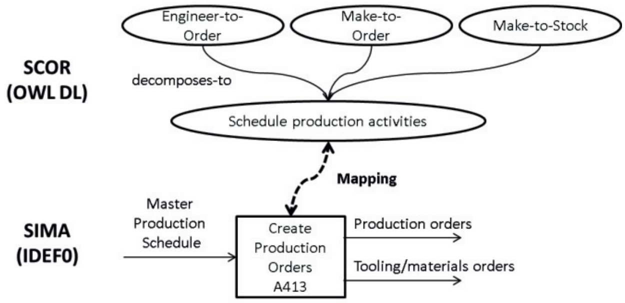

Fig 6. Mapping SCOR and SIMA

Table 2: Mapping between SMS goals and performance metrics and activities of interests

Name	Value	Source
SMS goal	Agility	SCOR
Goal definition	The ability to respond to external influences The ability to and speed of change	
Performance metric	Upside Make Flexibility	
Performance metric definition	The number of days required to achieve an unplanned sustainable increase in production with the assumption of no raw material constraints.	
Identified business processes	Engineer-to-Order (sM1) Make-to-Order (sM2) Make-to-Stock (sM3)	
Activities of interests	Create Production Orders (A413)	SIMA

3.2. Current manufacturing system representation

The SIMA architecture represents the current manufacturing system. Since SIMA architecture is a reference model it does not represent any specific manufacturing system, it is representative of the state of the practice. We use it as a baseline from which we can illustrate how new technologies will impact manufacturing practices. The new practices are described in the planned manufacturing system in the following section. As an example, Figure 3 shows the original *Create Production Orders* activity from the SIMA model and the planned activity model. Additional elements are colored blue to highlight the difference. Table 3 defines four of the ICOMs from the figure that are discussed further in our example.

Table 3: ICOM definitions for the current manufacturing system

Element	Definition	Category
Master Production Schedule	A list of end products to be manufactured in each of the next N time periods. The list specifies product IDs, quantities, and due dates.	Input
Planning Policies	The business rules by which the manufacturing organization does production planning including product prioritization, facility usage rules, make-to-inventory/make-to-order and selection of planning strategies.	Control
Tooling list	The complete tooling list for some batch of the part in exploded form, including all tools, fixtures, sensors, gages, probes, etc. The list identifies tool numbers, quantities, and sources. This list may include estimates for consumption of shop materials.	Control
Final Bill of Materials	The complete Bill of Materials for the part/product in exploded form, with quantities of all materials needed for some batch size of the Part. This may include any special materials which will be consumed in the process of making the part batch, such as fasteners, spacers, adhesives; alternatively those may be considered "shop materials" and included in the tooling list.	Control

3.2.1. Enhanced manufacturing system

To illustrate our mapping consider the following scenario for a company that manufactures gears. The company receives a customer order change request for one of their specialized gears. The required delivery date for this order is reduced by two weeks from the original production schedule. The gears are produced by specialized processes of either powder metal extrusion or hot isostatic pressing (HIP) method. The manufacturing system is constrained by the capacity of the specialized processes and the heat treating machine to satisfy this rush order request. With the current system, the company would risk losing the order because they would not be able to produce the product in the required time.

In the envisioned system, however, the company could look for partners to help where their own capacity is limited. A web-based registry of suppliers is used to quickly find capable partners in this new environment (MacArthus and Ameri. 2011). The digital representation of precise engineering and manufacturing information is used to specify production requirements for new partners (NIST. 2014; MIL-STD. 2013). These proposed enhancements to the system may very well make the company more competitive, but before attempting to introduce these changes the company must fully understand the implications. The method that we propose allows a company to understand how the business processes will be impacted and what performance metrics will be needed for that assessment, as well as what new information flows will be needed. In terms of information flows there are several notable changes in the current system.

For the planned system to identify capable suppliers a Request for Proposal (RFP) package is prepared and sent to a web-based supplier registry for quote. This package contains all the required product and process information necessary to respond to the RFP. Information includes, but is not limited to, CAD documents, bill of materials, quantity, due dates, product specifications, process technical data characteristics, and other information necessary to produce the part, assembly, or product. Other suppliers prerequisites' to qualify to quote are: supplier competency in the specialized processes, powder metal extrusion or hot isostatic pressing process, past quality performance history, capacity and sound financial standing. Qualified suppliers will be evaluated based on supply flexibility in make, delivery, delivery return, source, source return, and other qualifications.

Upon receipt of the RFP at the supplier registry, the performance metrics for measuring supply flexibility in make, delivery, delivery return, source, and source return are retrieved. Other secondary performance metrics can be used as required. This includes mapping the supplier capabilities with the performance metrics, matching supplier capability with RFP's evaluation criteria, and retrieving a list of capable suppliers that meet the performance evaluation criteria. Each supplier provides a price quotation to deliver the BOM's order quantity at the requested due date. The remaining activities are: simulate and predict the in-house manufacturing cost for the quantity specified in MPS (Master Production Schedule), determine an optimal ratio between supplier's purchasing and in-house production cost for each BOM, and finally plan and execute production orders.

For each supplier, a predictive model of the planned system provides a purchasing cost for all variations in the ratio of in-house production to outsourced from one to the quantity specified in MPS. The in-house manufacturing cost for the quantity specified in MPS can be simulated using a cost table. For all pairs of supplier's purchasing and in-house production costs, the minimum cost can be found. By exploding the BOM, individual items and consequent tooling and materials' orders are identified. Then, the optimal ratio between in-house and outsourcing is determined.

3.3. Planned manufacturing system representation

The SIMA model describes manufacturing activities at a level of detail that does not prescribe how to achieve the activities. Thus, in our method the activities are further decomposed into specific tasks. Figure 4 is a decomposition of the planned activity in Figure 3b with modifications which reflect how the activities are made more robust by the envisioned enhancements. The particular modification reflects the sourcing of capable suppliers more intelligently using the web-based registry as described above. To meet increased demand, production capacity is rapidly increased by identifying capable suppliers that meet the production requirements.

In short, the enhanced capabilities of the planned manufacturing system can be summarized as follows. First, using product and process data, the system discovers and retrieves a list of candidate suppliers who can manufacture the required product. Second, the system is able to predict both the purchasing and in-house production cost given the MPS. Based on the predicted costs, an optimal ratio of in-house production versus purchasing is determined. Finally, using the optimal ratio between in-house and purchasing, the system generates production, tooling, and materials' orders. Note that the activity *A4131 Retrieve capable suppliers* would be further decomposed to describe those details.

Table 4: Select elements in identified activity for a planned manufacturing system

Element	Current definition	Planned definition
Bill of materials (BOM)	The complete Bill of Materials for the part/product in exploded form, with quantities of all materials needed for some batch size of the Part. This may include any special materials which will be consumed in the process of making the part batch, such as fasteners, spacers, adhesives, etc.; alternatively those may be considered "shop materials" and included in the tooling list.	The BOM is used as an input to discover suppliers. The part number in the BOM is attached to supporting Computer-Aided Design (CAD) documents.
CAD documents	Not used in this activity	STEP (Standard for the Exchange of Product model data) is used to express 3D objects for CAD and product manufacturing information (ISO10303-1. 1994). This exchange technology enables the discovery of suppliers that can manufacture such parts.
Web registry of suppliers	Does not exist	This registry of suppliers stores supplier's information using MSC (manufacturing service capability) model which enables semantically precise representation of information regarding production capabilities (Vujasinovic et al. 2010)
Planning policy	The business rules by which the manufacturing organization does production planning. This includes product prioritization, facility usage rules, make-to-inventory/make-to-order and selection of planning strategies, e.g. Just-In-Time, Critical Inventory Reserve, etc.	The planning policy includes a decision making mechanism that determines an optimal ratio between purchasing and in-house production quantity. This extension allows enterprise to not only meet the customer demands with flexible capacity but also in most economical way.

3.4. Gap analysis

Performance assurance challenges to implementing an enhanced system fall into two categories: technology and performance measures. Once an enhanced system is planned, suitable technology can be sought to satisfy the new system. Table 5 illustrates some of the technology challenges for our example.

Table 5: Identified technology challenges

Activity	Challenges	Reference
Retrieve capable suppliers	Supplier capabilities need to be marked up using semantic manufacturing service model. Queries need to be generated automatically from product and process data	Kulvatunyou, Cho and Son. 2005
Predict purchasing cost Predict in-house manufacturing cost	Part cost needs to be predicted for new parts that have never been produced before	Deverlie and Castelain. 1999

To ensure the new system will actually improve performance, performance measures also need to be identified. The application of performance assurance principles through-out all phases and levels of manufacturing helps ensure that the manufacturing processes meet their intended functional requirements while providing necessary feedback for continuous improvement. Performance data must support the objectives of the manufacturer, from the highest organizational level cascading downward to the lowest appropriate levels. It is critical that these lower level measurements reflect the assigned work at their own level while contributing toward overall operational performance measurements for the enterprise.

For example, two key measures of performance, *manageable quantities* and *production cost* (defined in detail in the SIMA documentation), are significantly impacted in the planned system and more data is needed to calculate these in the new system. In the enhanced system the capacity that determines the manageable quantities becomes flexible by identifying capable suppliers via web. Once the production orders become a combination of in-house and purchasing, a decision needs to make on which orders will be sent out to bid. Secondly, determining the production cost is not a simple addition of costs between in-house and purchased parts. For example, quality may not be consistent with purchased parts. From the total cost point of view, this may result in more cost than expected due to inspection and customer claims. Thus, the concept of a cost is much more complex in the planned system. It is a comprehensive metric that is closely integrated with a predictive model to estimate the cost incurred in later stages of production and usage. The comparison of the activities relevant to above ideas is summarized in Table 6 and potential enablers for the enhanced capabilities of the planned manufacturing system are listed in Table 7.

Table 6: Activity design comparison

Current	**Limitation**	**Planned**
Create production orders for manageable quantities with specific due dates	Production orders may not be able to produce quantities with specific due dates given the capacity of resources	Rapidly identify capable suppliers on web who are capable of producing required products
Determine which orders will be produced in-house (and in what facilities) and which will be sent out to bid.	The determination of the ratio between in-house and outsourcing does not account for total cost of production including quality and inspection (Katja, Jämsen, and Paranko. 2002)	Determine an optimal ratio of which orders will be produced in-house and which will be sent out to bid based on the total cost of production

Table 7: Mapping between enhanced capabilities and potential enablers

Enhanced capabilities of the planned manufacturing system	**Potential enablers**	**Relevant current manufacturing system elements**
Semantically rich production and process information can help to dynamically discover capable suppliers using the product information of the required production	MIL-STD (MIL-STD-31000A;Lubell et al. 2013) ISO 10303 (ISO10303-1;Pratt. 2001) STEP-NC (Weck, Wolf and Kiritsis. 2001) MTConnect (Alturu and Deshphande. 2009)	Tooling list (Control) Final Bill of Materials (Control)
Manufacturing cost for the new parts that have never been produced before are initially unknown but need to be approximated	Predictive analysis models	Not used in this activity

4. Conclusion and future work

In conclusion, the proposed analysis method is an integrated approach that utilizes multiple reference models and formal representations to map strategic goals and operational performance metrics. A scenario that illustrates how a manufacturing operation might respond to an order that they are not able to fulfill in its entirety in house in the time frame needed was presented to illustrate the proposed analysis method. By replicating the proposed method for other performance goals and with other scenarios, a comprehensive set of challenges to SMS can be identified. Future work will explore ways in which those challenges can be systematically addressed, thereby reducing the risk for manufactures in introducing new technologies. In addition, the ontology described here, which is central to the methodology, has been prototyped. We plan to expand on that as more examples are developed. The ontology will serve a fundamental role in managing the system complexity as more SMS technologies are introduced and will be described further in future work.

Disclaimer

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