NISTIR 8108

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National Institute of
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# Performance Challenges Identification Method for Smart Manufacturing Systems

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**Abstract**
Smart Manufacturing Systems (SMS) need to be agile to adapt to new situations by using detailed, precise, and appropriate data for intelligent decision-making. The intricacy of the relationship of strategic goals to operational performance across the many levels of a manufacturing system inhibits the realization of 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 modeling 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 harmonized 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.

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## 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 [37, 43]. Along with these technologies, however, comes a greater need to be able to respond to information quickly [8] and effectively, thereby disrupting ongoing processes. SMS need to be agile to adapt to these challenges by using real-time data for intelligent decision-making, as well as predicting and preventing failures proactively [25, b]. 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 [6]. By putting in place a continuous performance assurance process, companies can ensure products are manufactured through verifiable manufacturing processes.

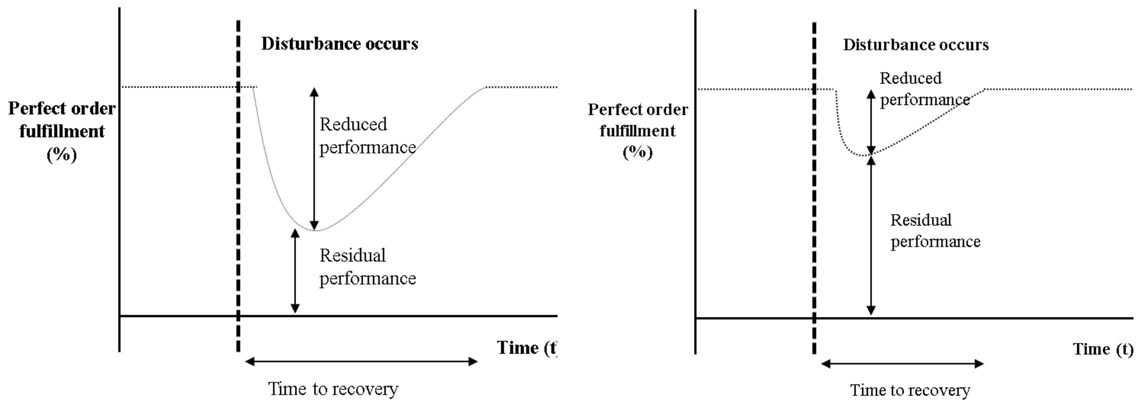
Both new and longstanding challenges at all levels of a manufacturing system inhibit the realization of SMS. The intricacy of describing these challenges stems from the grand complexity of manufacturing systems. This paper proposes a method for identifying challenges by focusing on a particular aspect of a manufacturing system. The proposed method integrates two existing models related to manufacturing operations:

- The Supply Chain Operations Reference (SCOR) from the Supply Chain Council (SCC) [45], and
- The manufacturing activity models from the Systems Integration for Manufacturing Applications (SIMA) Reference Architecture [4]

The goal of the SCC is to identify and promote best practices in the management and operation of supply chain activities across many industries. The SCOR reference model provides a standard language for characterizing individual supply-chain activities. 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 engineering and operational aspects of manufacturing a product from conception through production. For this research we have identified where the two models overlap when the business processes from SCOR directly correspond with the more technical, detailed and operational SIMA activities.

Our intent in harmonizing these two models is to illustrate how performance metrics from the business-focused SCOR model can be identified in the operational activities of the SIMA model. We base this mapping on the use of formal representation methods for defining both models. The SIMA model uses a formal activity modeling technique known as IDEF0. To formalize the SCOR model which is presented in plain English, we use the Web Ontology Language [35]. For IDEF0 which is a formal diagramming technique, we develop an ontology that facilitates the mapping between the different viewpoints of the two models.

Figure 1 depicts how performance metrics are identified in the SCOR context. 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 [34].




(a) Current manufacturing system (b) Planned manufacturing system

Figure 1. Illustrative manufacturing system performance

The agility goal is shown to be 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 goal [45]. In this paper, we explain how this 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. “Foundations” reviews the foundations to the proposed challenges identification method. We describe the challenges identification method in “SMS challenges identification method,” illustrate it with an example, and show how it can be used to identify challenges for performance assurance. “Discussion” provides discussion on the proposed method in the context of continuous improvement. Finally, we present our conclusion and discuss future work.

## 2. Foundations

In this section, we review the use of the two formal representation methods used in the proposed challenges identification method: the Web Ontology Language (OWL) [35] and IDEF0 [19] models.

### Harmonization of SCOR and SIMA via ontology

We develop an ontology to represent the SCOR model and the SIMA activity model. Originally, the SCOR model is presented in plain English, whereas the SIMA activity model is represented in IDEF0.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 [15]. An ontology is a set of shared definitions of classes, properties and rules describing the way those classes and properties are employed.

In this paper, we use the following notations for ontological constructs: classes, which represent the concepts being captured in **Bold**, the properties, which describe the concepts are in Italics with leading character in lowercase (*groups*); and individuals—instances of the concepts reflecting the real world example are in Italics with leading character in uppercase (*Upside_Make_Flexibility)*.

There are three main benefits of encoding the reference models in OWL: 1) structural support for harmonization of existing information 2) querying capability and 3) reasoning capability. Structural support for harmonization of existing information is not discussed in detail for this paper but the capability of the resulting ontology acquired from the harmonization is discussed in the context of building the classification for manufacturing operations from SCOR's process model and SIMA's activity model. Querying capability is illustrated in this paper in "Scope determination." It is used to help scope the analysis. Lastly, reasoning capability is briefly highlighted below.

The SCOR model is published as a nearly 1 000 page long document. The publisher, APICS (American Production and Inventory Control Society), recommends two days of intensive training to learn the structure, interpretation and use of SCOR framework elements. Representing this information using OWL provides improved accessibility to users, tools and knowledge engineers [3].

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 hierarchical definitions which are interconnected with each other. Each of the abstract concepts is hierarchically decomposed 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. The performance component consists of performance attributes and performance metrics. A performance attribute is a grouping or categorization of performance metrics to express a strategic goal. Table 1 provides the complete list of performance attributes in SCOR.

Table 1. Performance attributes in SCOR [45]

| **Performance Attribute** | **Definition** |
|---|---|
| Reliability | The ability to perform tasks as expected. Reliability focuses on the predictability of the outcome of a process. |
| Responsiveness | The speed at which tasks are performed. The speed at which a supply chain provides products to the customer. |
| Agility | The ability to respond to external influences, the ability to respond to marketplace changes to gain or maintain competitive advantage. |
| Costs | The cost of operating the supply chain processes. This includes labor costs, material costs, management and transportation costs. |
| Asset Management Efficiency (Assets) | The ability to efficiently utilize assets. Asset management strategies in a supply chain include inventory reduction and in-sourcing vs. outsourcing. |

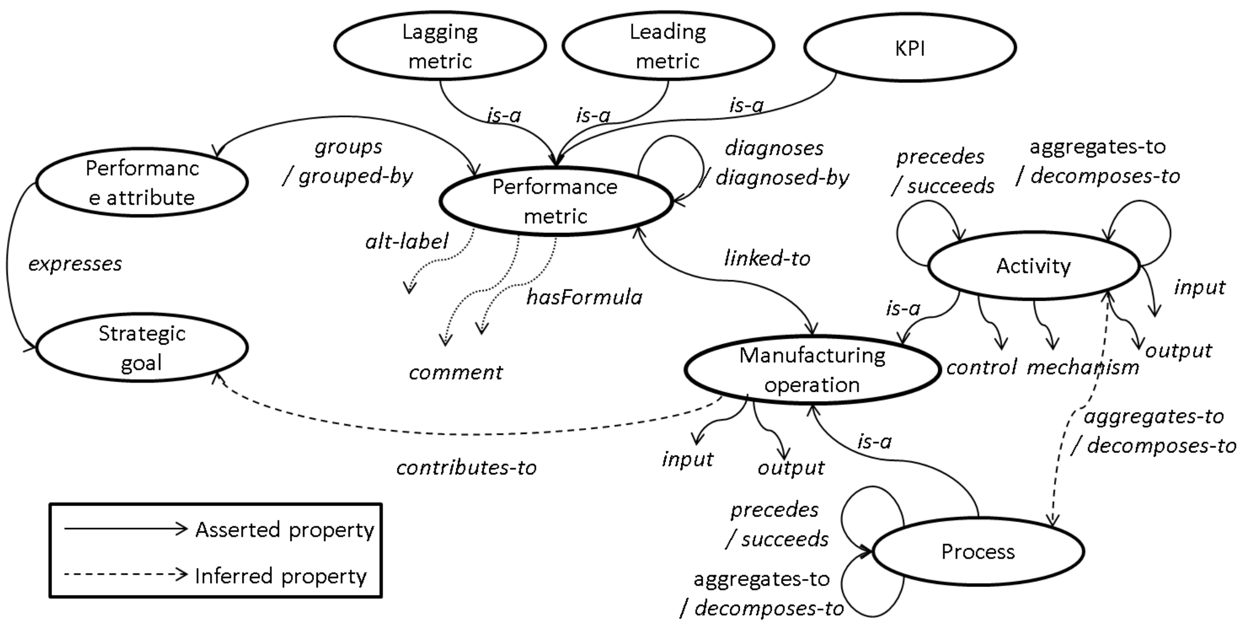



Figure 2. High level view of the harmonization ontology

These performance attributes are used to express the strategy for a manufacturing system. A **Strategic goal (SG)** is expressed by weighted **Performance attributes (PA)**.

$$SG_i = w_1(Reliability) + w_2(Responsiveness) + w_3(Agility) + w_4(Costs) + w_5(Asset\ management\ efficiency).$$

This can be interpreted as a multiple criteria decision-making (MCDM) problem in itself [16, 23]. Most MCDM problems consider the use of criteria to assess effectiveness of a selection against a defined problem. Criteria can be used to structure complex problems well by considering the multiple criteria individually and simultaneously.

Figure 2 illustrates the high level view of the ontology we developed to harmonize the SCOR and the SIMA model. The SIMA activities are represented using the **Activity** class in the ontology. The ontological constructs enable the mapping between strategic objectives and operational activities. For the purpose of identifying challenges to SMS, only select components of the reference models depicted in Figure 2 are used in the examples. In addition, the illustrated example provided in this paper only considers one performance attribute--agility.
Note that what is referred to as activities in SIMA are very similar to the processes in the SCOR model. **Process** and **Activity** are related using the *aggregates-to/decomposes-to* object property in Figure 2. In this paper, the details of the harmonization of the two models are not discussed but rather the method. In brief, all the activities in the SIMA activity model are encoded as individuals of **Activity**, which is a subclass of **Manufacturing operation**. An activity's name is represented as an individual's label. Parent and child activities are related using the object property *aggregates-to/decomposes-to*.

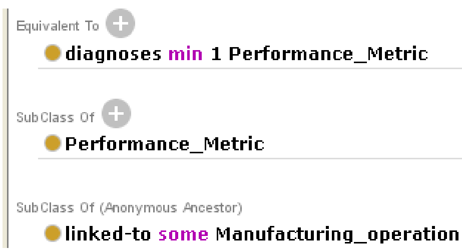
Figure 2 also provides representation of how a **Manufacturing operation** is defined in the harmonization ontology. Inputs, controls, outputs and mechanisms of an activity in the SIMA model are classified into inputs of a manufacturing operation. **Activity** from the SIMA model and **Process** from the SCOR model are both subclass of **Manufacturing operation** and, therefore, inherit the same properties. Also, **Activity** and **Processes** are related using *aggregates-to/decomposes-to*, which is the same object property used for parent/child relationships in the SIMA activity model and for capturing the interrelations in the SCOR's process hierarchy model. The ontology facilitates this semantic mapping and enables the proposed performance challenges identification method to focus on very specific activities.

Table 2. An example of reasoning provided by the ontology

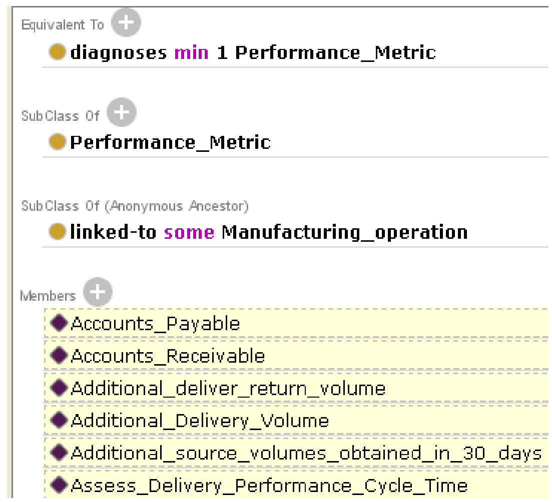
| | |
|---|---|
| **Aim** | Infer that a performance metric that diagnoses other performance metrics is a leading performance metric |
| **Classes** | **Performance metric**, **Leading metric** |
| **Properties** | *diagnoses* (Domain: **Performance metric**, Range: **Performance metric**) |
| **Restriction** | On **Leading metric**: *diagnoses* min 1<br>(a performance metric must be a Leading Metric if it is related with at least 1 performance metric) |
| **Input** | An individual of **Level-3 Metric** (Current Purchase Order Cycle Times) is not diagnosed by any other **Performance metric** |
| **Output** | *Current Purchase Order Cycle Times* is classified as an individual of the class Leading Metric in addition to explicitly stated **Level-3 Metric** |

Finding the correct performance metrics has always been a difficult task. It is important to measure both the bottom-line results of manufacturing processes, as well as how well the manufacturing system will perform in future. For this reason, companies often use a combination of lagging and leading metrics of performance. A lagging metric, also known as a lagging indicator, measures a company's performance in the form of past statistics. It's the bottom-line numbers that are used to evaluate the overall performance.

The major drawback to only using lagging metrics is that they do not tell how the company will perform in the future.  A leading metric, also known as a leading indicator, is focused on future performance. For simplicity, we qualify leading metrics as metrics that diagnose at least one other metric. A performance metric can be lagging and/or leading depending on the circumstances. Table 2 explains the rules embedded in the ontology to infer and classify performance metrics into lagging and/or leading. Figure 3 shows the implementation in Protégé 4.3 [44]. The query is written based on the Manchester OWL syntax [54]. One can only execute a query on an ontology after a reasoner (a.k.a. classifiers) is selected. In the following example, we used the Pellet reasoner [42].




(a) Before reasoning (Leading_Metric)




(b) After reasoning (Leading_Metric)

Figure 3. The difference in classification of individuals' membership before and after the inference

Figure 3b shows that **Leading_Metric** has new individuals after reasoning. The aim described in Table 2 is fulfilled by reasoning. This type of inference is not limited to classifying leading and lagging metrics.  For example, individuals of **Performance_Metric** can be classified into a new class called **KPI (Key Performance Indicator)**, when we have a logical and agreed upon definition for the concept KPI and the ontology captures properties that distinguish KPIs from other performance metrics. These illustrated and potential classifications highlight the reasoning capability using OWL to represent the SCOR and the SIMA model for the purpose of finding the correct performance metrics.

**Representation of activities via IDEF0**

The IDEF0 definition of a function is ''a set of activities that takes certain inputs and, by means of some mechanism, and subject to certain controls, transforms the inputs into outputs." IDEF0 models consist of a hierarchy of interlinked activities in box diagrams with defined terms. 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. Figure 4 shows the basic IDEF0 representation with its primary interfaces. The decomposition of activities is represented using a numbering scheme. Numbers appear in the lower right corner of the box. Decomposed activities are always prefaced with the number of their parent activity.

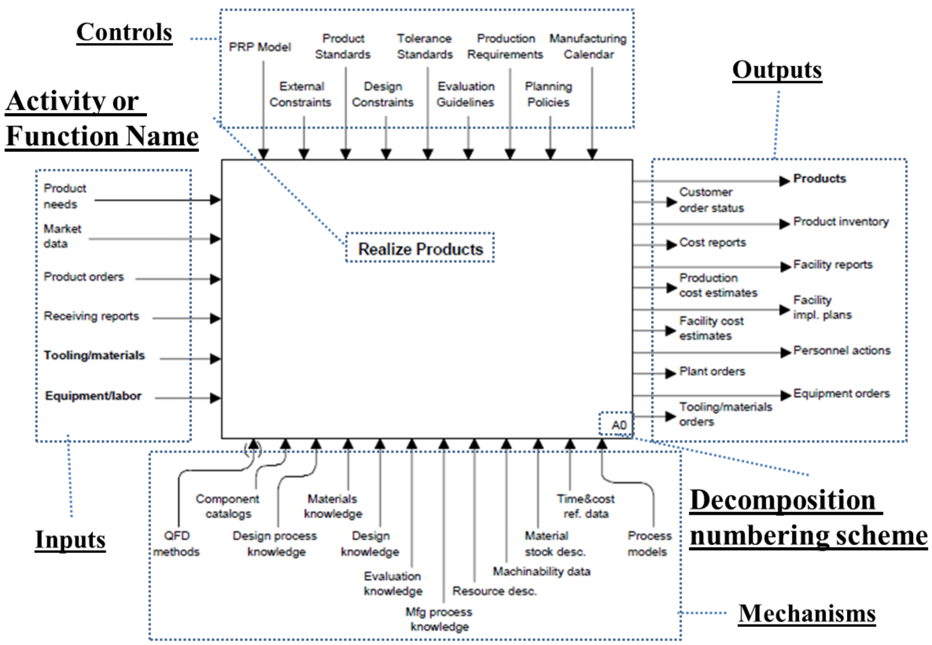
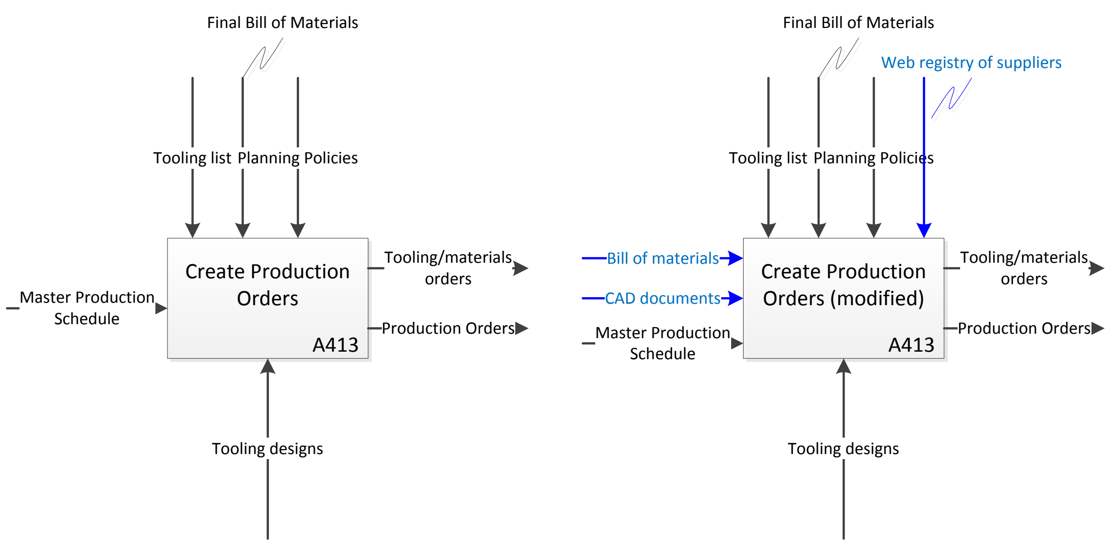



Figure 4. Basic IDEF0 representation of an activity and its related information overlaid on SIMA A0




(a) Current activity from SIMA's A413 (b) Planned activity

Figure 5. Activity of interest

Using SIMA to identify challenges, the IDEF0 function represents an activity of interest in the proposed challenges identification method. The activity of interest is subject to modifications to meet the strategic goal. Figure 5a 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 mechanisms on the activity.

Figure 6 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. Figure 5b and 6 depict the modified version of the original A413 activity, and are discussed in depth in "Planned manufacturing system representation."

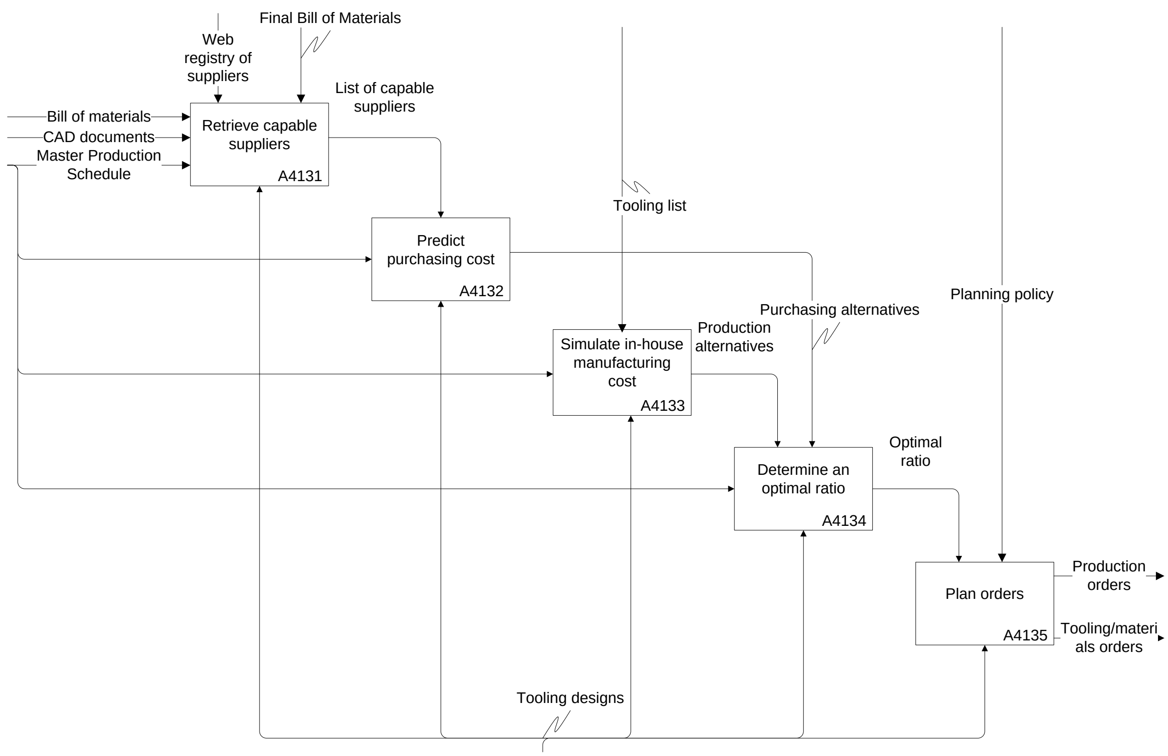



Figure 6. Planned activity model decomposed

## 3. SMS challenges identification method

One of the drivers for smart manufacturing is the need to respond to changes in demand more quickly and efficiently [10, 52]. For example, we consider 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. In this scenario, we postulate that the manufacturer could fill the order by outsourcing a portion of the production needs through the use of smart manufacturing technologies, which 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 modeling of complex manufacturing systems [13] and is the objective of our challenge 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. This helps to relate high-level strategic goals and requirements to low-level operational activities and provides the means to understand and represent interrelationships among the different elements of a manufacturing system. Further, the method supports effective communication across a manufacturing organization.

Table 3. The proposed challenges identification method

| | | |
|---|---|---|
| Task 1<br>Determine scope of the challenges identification analysis | Explanation | Identifies manufacturing operations and performance metrics relevant to the scope |
| | Input | A strategic goal of a manufacturing system (Figure 7a) in query |
| | Output | A set of manufacturing operations and performance metrics relevant to the specified strategic goal (Figure 7a,b) |
| Task 2<br>Represent current manufacturing system | Explanation | Represent the identified manufacturing operation formally |
| | Input | An identified manufacturing operation (Figure 7b) |
| | Output | A set of activities from the current manufacturing system (Figure 5a) |
| Task 3<br>Represent planned manufacturing system | Explanation | Define the modifications to the current manufacturing system to improve the identified performance metrics |
| | Input | An identified activity and a set of performance metrics relevant to the specified strategic goal (Figure 5a) |
| | Output | An improved activity from the planned manufacturing system (Figure 5b and 6) |
| Task 4<br>Gap analysis | Explanation | Compare the activity models of the current and the planned manufacturing system to highlight implementation barriers |
| | Input | An activity from the current manufacturing system and the corresponding improved activity from the planned manufacturing system (Figure 5b and 6) |
| | Output | An analysis of implementation barriers for current manufacturing system (Table 8, 9) |

*Note that Activities are subset of Manufacturing Operations

Table 3 shows the proposed challenges identification method that integrates SCOR, SIMA Reference Architecture, and scenario-based validation. In Table 3, we provide references within parentheses to illustrated examples in this paper.

To determine a scope of analysis, 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 we used to represent the current manufacturing system. We then create a planned manufacturing system activity model to identify modified 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 the planned system identifies challenges in the specific terms associated with the activity models. Table 3 summarizes these steps and they are illustrated below in the context of an example based on the Create Production Order activity.

**Scope determination**

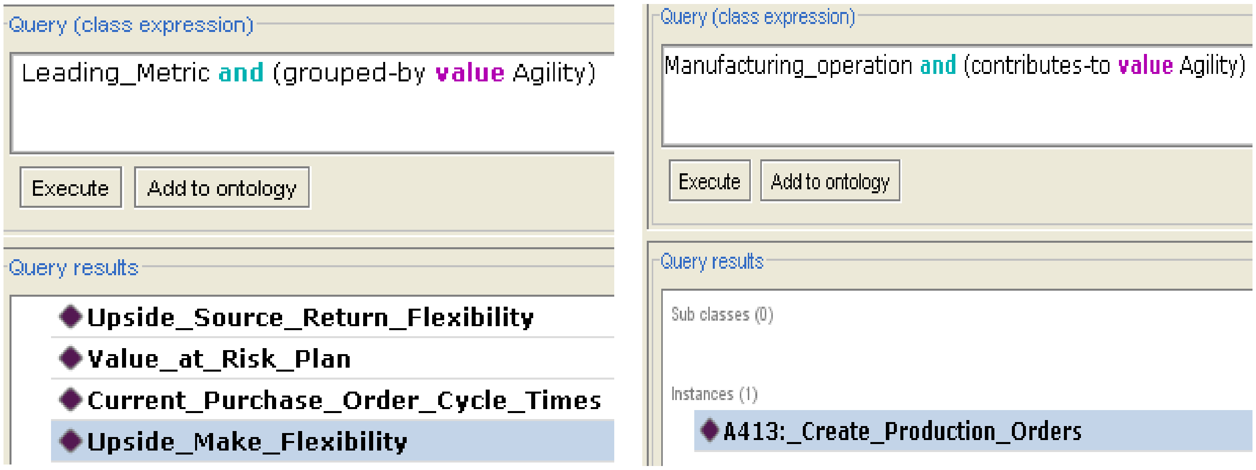
This section highlights the query capability of the ontology as a key enabler to the proposed method. To evaluate performance with respect to SMS goals, we identify specific manufacturing operations that contribute to a goal and subsequently the activities which support those manufacturing operations. The SMS concept has several goals including agility, productivity, sustainability and others [17, 38]. In this paper, agility is selected to test the proposed challenges identification method.

The result of the following series of queries and mappings defines the scope for our analysis. Figure 7a shows the results of querying the ontology to find leading metrics to the agility goal. Query #1 "What are the leading performance metrics to be monitored for agility?" is written in DL Query [54] as follows: **Leading_Metric** and (*grouped-by value Agility*). Performance metrics are organized hierarchically. One can drill down into lower levels of the hierarchy for one of the agility performance metrics, *Upside_Make_Flexibility*, to find the lower level metrics associated with the agility goal and to find processes associated with those metrics. *Current_Make_Volume* is one of the lower level metrics one can choose to investigate. If one chooses to investigate a performance metric at high level, the subsequent analysis and the identified challenges will likewise be at high level. Query #2 "What are the low-level manufacturing operations associated with agility goal?" is written in DL Query as follows:

**Manufacturing_operation** and (*contributes-to* value *Agility*). The query results are partially shown in Table 4. Figure 7 shows the implementation of the queries. We identify generic processes that are important to agility: *Engineer-to-Order*, *Make-to-Order* and *Make-to-Stock*. These identified processes can be drilled down into the activity *Create Production Orders.* One of the explanations for this mapping is shown in Figure 8. *Create Production Orders* is related to *Engineer-to-Order* with an object property *aggregates-to* (line 3). *Engineer-to-Order* is linked-to *Upside_Make_Adapatability* which is grouped-by *Agility* (line 8, 9). A new property between *Create Production Orders* and *Agility* is inferred based on line 5, which chains several object properties into one object property.

Table 4. DL query condition and query results

| | |
|---|---|
| **Query result #1** | *Additional source volumes obtained in 30days, Customer return order cycle time reestablished and sustained in 30days, Upside Deliver Return Adaptability, Upside Source Flexibility, Downside Source Adaptability Upside Deliver Adaptability, Current Deliver Return volume, Percent of labor used in logistics not used in direct activity, Current Make Volume Supplier's/Customer's/Product's Risk Rating, Upside Deliver Flexibility, Value at Risk Make, Upside Source Return Flexibility, Value at Risk Plan Current Purchase Order Cycle Times, Value at Risk Deliver, Demand sourcing supplier constraints, Upside Make Adaptability, Upside Source Return Adaptability, Downside Make Adaptability, Value at Risk Source, Upside at Risk Return, Additional Delivery Volume, Current source return volume, Percent of labor used in manufacturing not used in direct activity* |
| **Query result #2** | SCOR Process: *Receive Product, Mitigate Risk, Schedule Product Deliveries, Checkout, Route Shipments, Route Shipments, Process Inquiry and Quote, Stage Finished Product, Package, Authorize Defective Product Return, Receive product at Store, Receive Defective Product includes verify, Ship Product, Schedule Defective Product Shipment, Release Finished Product to Deliver, Identify Sources of Supply, Issue Sourced/In-Process Product, Enter Order commit Resources and Launch Program, Schedule Installation, Waste Disposal, Build Loads, Invoice, Request Defective Product Return Authorization, Verify Product, Receive and verify Product by Customer, Schedule MRO Return Receipt, Issue Material, Receive Excess product, Load Product and Generate Shipping Docs, Finalize Production Engineering, Schedule Excess Return Receipt, Receive MRO Product, Quantify Risks, Identify Risk Events, Return Defective Product, Deliver and/or Install, Pack Product, Transfer Excess Product, Stage Product, Transfer MRO Product, Transfer Defective Product, Authorize MRO Product Return, Receive Configure Enter and Validate Order, Generate Stocking Schedule, Evaluate Risks, Identify Defective Product Condition, Produce and Test, Pick Product, Obtain and Respond to RFP/RFQ, Negotiate and Receive Contract, Stock Shelf, Transfer Product, Authorize Supplier Payment, Disposition Defective Product, Schedule Production Activities, Establish Context, Fill Shopping Cart, Authorize Excess Product return, Receive Enter and Validate Order, Consolidate Orders, Select Final Supplier and Negotiate, Release Product to Deliver, Reserve Inventory and Determine Delivery Date, Select Carriers and Rate Shipments, Receive Product from Source or make, Load Vehicle and Generate Shipping Documents, Pick Product from backroom, Install Product* |
| | SIMA Activity: *Create Production Orders* (illustrative) |




(a) A DL query for retrieving leading metrics

(b) A DL query for retrieving low-level manufacturing operation

Figure 7. DL query and query results on Protégé 4.3 (illustrative)

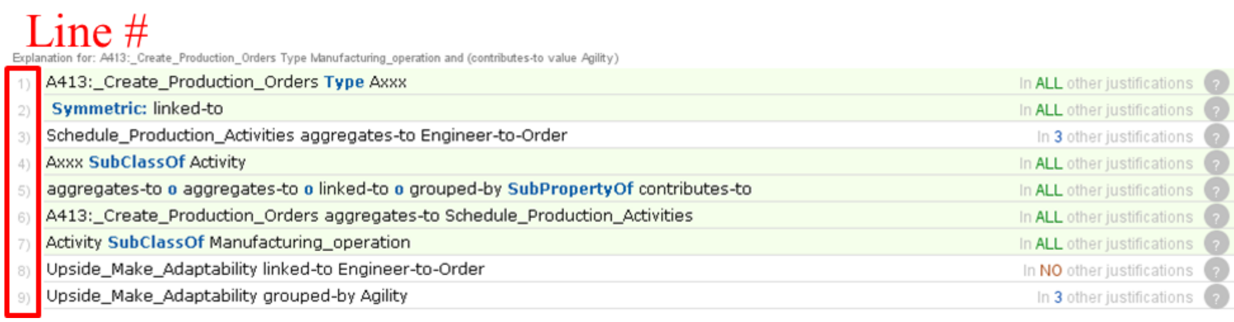



Figure 8. An inference explanation for the mapping between SIMA activity and SCOR process

The identified operational activities are subject to redesigning for improvement. By redesigning the identified operational activities, the manufacturing system is assumed to be more capable of satisfying strategic objectives [9]. The redesign of the activities incorporates new and emerging capabilities that are the foundation of Smart Manufacturing. New capabilities from machine sensors to internet-enabled supply chains are emerging every day and can improve manufacturing operations. We provide a demonstration of this redesigning for improvement with the following example in the sections below-- “Current manufacturing system representation” and “Planned manufacturing system representation.”

**Current manufacturing system representation**

A manufacturing system is defined as the configuration and operation of its subelements such as machines, tools, material, people and information to produce a value-added physical, informational or service product [9]. The SIMA architecture represents the current manufacturing system.  While this model 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 5a shows the original Create Production Orders activity from the SIMA model and the planned activity model. Additional elements are highlighted in Figure 5b to show the difference. Table 5 defines four of the ICOMs from the figure that are discussed further in our example.

Table 5. 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. 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 (BOM) 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 |

**Enhanced manufacturing system**

To illustrate our approach 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. HIP is similar to the process used to produce powder metallurgy steels. Heat treating of gears is also a required process step. 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 would 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 [2]. The digital representation of precise engineering and manufacturing information is used to specify production requirements for new partners [31, 37]. 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. A web-based supplier registry contains a supplier-capability database.

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 the 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.

We have defined formal representations of performance metrics and performance goals for agility, their relationships and properties. The performance metrics are supply flexibility in make, delivery, delivery return, source, and source return. Based on the harmonization ontology concepts, definitions, relationships and properties, we implemented the mapping between performance goals and performance metrics.
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 the MPS. The in-house manufacturing cost for the quantity specified in the MPS can be simulated using a cost table. For all pairs of outsourcing 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.

Table 6. 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; 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 [21]. This exchange technology enables the discovery of suppliers that can manufacture such parts. Alternatively, Web Computer Supported Cooperative Work (CSCW) to translate CAD and FEA (Finite Elements Analysis) data into VRML (Virtual Reality Markup Language) can provide an easy-to-access to mechanical-design-and-analysis in a collaborative environment [11, 48, 55]. |
| Web registry of suppliers | Does not exist | This registry of suppliers stores supplier's information using MSC (manufacturing service capability) model. The MSC model enables semantically precise representation of information regarding production capabilities [11, 28, 29, 30, 49, 50] |
| 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. | The planning policy in the planned system may include a decision-making mechanism that determines an optimal ratio between purchasing and in-house production quantity. This extension allows the enterprise to not only meet the customer demands with flexible capacity but also in the most economical way. |

**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. This conceptual design through further decomposition is crucial to defining new creative manufacturing systems [32]. Figure 6 is a decomposition of the planned activity in Figure 5b with modifications that 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. A sample of enhanced capabilities is given in Table 6. Note that these enhanced capabilities are only for demonstration purposes and does not imply that these are the best for the purpose. Other of alternatives such as simulation-based integrated production planning approach [26] and SOA-based configurable production planning approach [27] are possible.

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.

**Gap analysis**
Challenges to assuring the performance of 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 7 illustrates some of the technology challenges for our example.

Table 7. Identified technology challenges

| Activity | Challenges | Reference |
|---|---|---|
| Retrieve capable suppliers | Supplier capabilities are marked up using semantic manufacturing service model. Queries are generated automatically from product and process data | [7, 24, 28, 46] |
| Predict purchasing cost<br>Predict in-house manufacturing cost | Part cost are predicted for new parts that have never been produced before | [12, 14, 33, 47, 51] |

To ensure that the new system will actually improve performance, performance measures need to be identified.  The application of performance assurance principles through-out all phases and levels of manufacturing help 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 the web. Once the production orders become a combination of in-house and purchasing, a decision needs to be made 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 the above ideas is summarized in Table 8 and potential enablers for the enhanced capabilities of the planned manufacturing system are listed in Table 9.

Table 8. Manufacturing system design comparison

| **Current activity design** | **Limitation** | **Planned activity design** |
|---|---|---|
| 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 | 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 9. 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 [31]<br>ISO 10303 [21, 40]<br>STEP-NC [22]<br>MTConnect [36] | Tooling list (Control)<br>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 [41] | Not used in this activity |

## 4. Discussion

This section discusses the proposed method in the context of larger practice, the continuous improvement process. We acknowledge that the proposed method has limitations. Then, we lay out the plans for improving the proposed method.
The proposed method is based on an ontology that explicitly represents the relationship between high-level strategic goals and requirements to low-level operational activities. This provides the means to understand the interrelationship among the elements of a manufacturing system at multiple levels. The method also provides a potential means to communicate across a manufacturing organization. More importantly, it clearly distinguishes between what (goals) and how (manufacturing system design). This powerful capability, however, has innate limitations in the design. In addition, there are areas in the proposed method that require further validation to assure performance of a manufacturing system.

Figure 9 shows the identification of performance challenges in the context of a continuous improvement process [5]. The proposed method helps to specify what needs to be considered to meet a strategic goal. Performance metrics associated with a strategic goal and respective manufacturing operations at all levels of a manufacturing system are retrieved. A planned system is a configuration of a manufacturing system known and available. Users' expertise sets the boundary for available configurations. The resulting configuration is expected to meet the strategic goal. Therefore, planned manufacturing systems are subject to expertise of the users, which is unaccounted for in the scope of the method. Figure 9 also has the shading that the proposed method addresses.

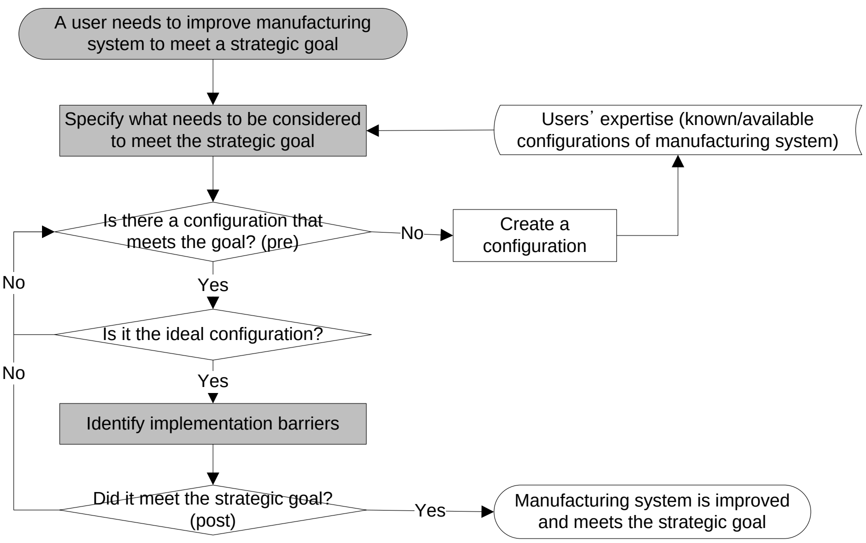



Figure 9. Performance challenges identification in the context of continuous improvement process

**Reference models validity**

SCOR and SIMA may not capture all possible strategic goals and manufacturing operations required for the performance challenges identification. In other words, agility in the SCOR model cannot be representative of all agility concepts used in practice. Table 10 shows similar but not identical definitions for agility from various sources.

Table 10. Agility definitions

| Sources | Definition |
|---|---|
| Dictionary | Definition for agile<br>Marketed by ready ability to move with quick easy grace<br>Having a quick resourceful and adaptable character [1]. |
| SCOR model | The ability to respond to external influences, the ability to respond to marketplace changes to gain or maintain competitive advantage [45]. |
| IEC 62264-1 | Agility in manufacturing is the ability to thrive in a manufacturing environment of continuous and often unanticipated change and to be fast to market with customized products. Agile manufacturing uses concepts geared toward making everything reconfigurable [20]. |
| Wiendahl model | Agility means the strategic ability of an entire company to open up new markets, to develop the required products and services, and to build up necessary manufacturing capacity [53]. |

Likewise, the manufacturing operations defined in the ontology do not account for all the manufacturing operations. The ontological structure provides means to harmonize reference models to better characterize such concepts with more detail.

We chose the SIMA model to represent manufacturing operations but actual systems will vary. We also need to better understand the relationship among the low-level activities and performance metrics as well. They not only have impact on the high-level strategic goals, but they also interrelate with each other. For example, increasing the batch size influences the average work-in-progress; changing the supplier portfolio affects the quality of the product. Ultimately, designing a manufacturing system should account for the interrelationships between low-level activities and performance metrics as well as their relation to high-level strategic goals.

**Method validity**

The proposed method does not assure that the planned system actually meets the specified strategic goal. Or, the planned system may not be the ideal configuration for the given strategic goal. This validation and evaluation of a planned system corresponds to "Is it the ideal configuration?" "Identify implementation barriers," "Did it meet the specified strategic goal?" in the Figure 9. Thus, it is logical to provide a means to further validate and evaluate the planned system. Various technologies can be used in this regard including physical testbed construction, simulation, mathematical formulation of the planned system and others. Physical testbeds enable validation of the planned system by collecting data from a shop floor for analytical use. This proposed method is only a starting point for system enhancement.

## 5. Conclusion and future work

Smart Manufacturing Systems (SMS) are characterized by their capability to make performance-driven decisions based on appropriate data; however, this capability requires a thorough understanding of particular requirements associated with performance across all levels of a manufacturing system. The proposed method uses standard techniques in representing operational activities and their relationship with strategic goals. This paper proposed a method to systematically identify operational activities given a strategic goal. It is an integrated approach that uses multiple reference models and formal representations to identify challenges for enhancing existing systems to take into account new technologies. A scenario that illustrates how a manufacturing operation might respond to an order that it is not able to fulfill in-house in its entirety in the time frame needed was presented. We demonstrated the proposed method with that scenario. By replicating the proposed method for other performance goals and with other scenarios, a more comprehensive set of challenges to SMS can be identified.

Future work will 1) replicate the proposed method for other performance goals 2) validate the proposed method discussed in "Discussion" and 3) explore ways in which the identified challenges can be systematically addressed, thereby reducing the risk for a manufacturer to introduce new technologies. We plan to expand on the ontology 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.

## 6. Acknowledgement

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## 7. Disclaimer

Certain commercial products in this paper were used only for demonstration purposes. This use does not imply approval or endorsement by NIST, nor does it imply that these products are necessarily the best for the purpose.

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