Towards a Road-Mapping Ontology for Open Innovation in Smart Manufacturing

Nenad Ivezic*, Miroslav Ljubicic
Systems Integration Division
Engineering Laboratory
NIST
Gaithersburg, MD, USA
{nenad.ivezic|miroslav.ljubicic}@nist.gov

***Abstract*— In nascent areas, such as Smart Manufacturing, new collaborative research and development programs (R&D) are frequently formed with the goal to ignite the innovation lifecycle. Yet, clearly formulating common goals and enabling shared understanding of key concepts, which are critical to achieving these goals, often involve long, drawn-out processes. These processes typically involve road-mapping that meet the need for informal, albeit imprecise and ambiguous, communications. We are starting to develop a road-mapping meta-model and an associated ontology to provide more precise and less ambiguous communications in a recently started R&D program on Smart Manufacturing. To that effect, in this paper, we analyze use cases to provide input into the meta-model and ontology development.**

Keywords - innovation; smart manufacturing; road-mapping; ontology; requirements; meta-model

I. Introduction

An essential task in R&D programs is to enable effective communication among the members of an emerging community, allowing efficient R&D program management, and open innovation processes. Traditionally, new R&D programs have been served well by developing road maps of planned activities. Such road maps often meet the need for informal, albeit imprecise and ambiguous, communications in emerging, cross-disciplinary communities. These communications issues can delay the completion of the road map considerably and inhibit the innovation process. For that reason, we explore Knowledge Technologies (KT) to enhance collaboration and communication in newly formed R&D programs by addressing the imprecision and ambiguity issues in road-mapping.

Our intention is to use KT to capture and represent the definitions of goals, issues, approaches, and other key concepts as information objects. We intend to share these concepts using new standards and available communication technologies. In doing so, we hope to achieve two goals. The first is to speed-up and improve the process of aligning different interpretations of these concepts. The second is to simultaneously reduce the number of interpretation conflicts that could impede that process.

In this paper, we lay a foundation for achieving those goals, and enabling collaboration, in a specific context: a new R&D program for Smart Manufacturing. That foundation will help in establishing an 'upper' ontology, which models key concepts in a 'generic' innovation process. That model helps to identify and enrich fundamental concepts and relationships that advance precision and remove ambiguities in communication within collaborating communities.

II. Requirements

A recently started R&D program drives our exploration of KT for collaborative R&D program management. We adopt a traditional road-mapping framework as a base in addressing the need for shared concepts in the program management. We point to an opportunity to enrich the framework to address precision and ambiguity issues.

A. A New SM R&D Program – Enabling Composable Apps

National Institute of Standards and Technology (NIST) has initiated an R&D program to advance science of systems integration towards the vision of composable SM systems [1].

The new program explores the potential for provisioning of manufacturing services as unbundled "apps," which could be significantly more flexible and less expensive to use than the current monolithic manufacturing applications. However, integrating heterogeneous services is not a trivial job. In April 2016, NIST hosted a workshop, called *Drilling down on Smart Manufacturing -- Enabling Composable Apps*, to work with industry and academia on the technical and standards-based solutions that will be needed. A road-mapping effort is planned to enable effective collaboration in this growing community.

B. Road-mapping Concepts for Innovation Management

Road-mapping exercises are a common practice when initiating collaborative work in new, government-funded, R&D programs; cross-industry, technology-development efforts; and, company-specific innovation activities [2-5]. To help organize these exercises, a conceptual architecture for road-mapping has been previously proposed [6]. Figure 1 shows a view of the basic concerns addressed in the architecture. These concerns provide a base for understanding the kinds of communications needed in a collaborative, open, innovation setting. That setting requires consistent views of the (1) business/market context, which addresses the "why" questions, (2) system/product/service context, which addresses the "what" questions, and (3) technology/R&D capability contexts, which addresses the "how" questions.

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* Corresponding author

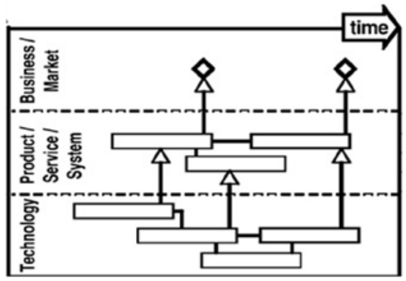

Figure 1. A Road-mapping Conceptual Architecture (after Phaal [6])

Using these road-mapping concepts, our requirements for shared conceptualization can be expressed with the following competency questions (CQs) [7]:

1) What Business Feature is of interest? A business feature is a specific characteristic of either a market driver or an enterprise driver of concern to the innovation effort.

2) What System Feature is of interest? A system feature is a characteristic of an implementable and usable artifact (such as a product, service, or system) that provides a desired effect with respect to a business feature of interest within the innovation effort.

3) What Technology (hereafter, Capability) Feature is of interest? A capability (technology or R&D resource) feature is an aspect of a capability that provides a desired effect with respect to a system feature within the innovation effort. It can be thought of as knowledge embedded in an artifact (either physical or informational) that provides some purposeful behavior with respect to an intended system function.

4) What System Feature enables a specific Business Feature? A system feature enables business features by way of some desired effect (often referred to as system function).

5) What Capability Feature enables a specific System Feature? A capability feature enables one or more system features by way of some purposeful behavior, enabling the system function.

These questions are typically answered in an informal, imprecise, and ambiguous way when embarking on a traditional road-mapping effort. As an innovation effort matures, however, there is a need to make these answers more formal, more precise, and less ambiguous. This need can be met by a communication based on a richer set of concepts.

For example, in the NIST Smart Manufacturing R&D program, we have elaborated the three major concepts in Figure 1 as follows:

1) Business Feature: Efficient, usable messaging standards management processes.

2) System Feature: Messaging standards life cycle management (LCM) System.

3) Capability Feature: Business process model variability management method.

The following questions also arose from these elaborations.

1) What *key aspects* of efficient, usable messaging standards management processes describe desired business-level improvement for the intended innovation?

2) What are *key aspects* of messaging standards life cycle management (LCM) system for the intended innovation?

3) What are *key aspects* of the business process model variability management method for the intended innovation?

4) What is the *essential way* the messaging standards life cycle management (LCM) system impacts the efficient, usable messaging standards management processes?

5) What is the *essential way* the business process model variability management method aspects impact the messaging standards life cycle management (LCM) system aspects?

C. Enriching Road-mapping Concepts for Innovation

The following high-level CQs capture the general direction regarding requirements for enhanced shared conceptualization:

1) What properties effectively describe Business Features?

2) What properties effectively describe System Features?

3) What properties effectively describe Capabilities?

4) What properties effectively describe System Features enabling Business Features?

5) What properties effectively describe Capabilities enabling system Features?

III. DEVELOPMENT

In this section, we introduce new concept and relationship to support enriched communication in open innovation processes, leading to new competency question (CQ) types.

A. Developing Enriching Road-mapping Concepts

We saw how a traditional road-mapping framework provides a good basis to which enriching concepts can be added. We derived both general CQs and directions for specific CQs for communication about innovation processes.

We now propose an ontological structure to capturing and modeling those enriching concepts. We find inspiration for the enrichment from the research done in characterizing Behavior and Function concepts for product design and engineering [8]. The following properties are introduced in support of CQs:

1) What properties effectively describe Business Features?

a) Type: Is the business feature an external (market) or internal (enterprise) driver?

b) Performance: A measure of improvement of business utility due to the business feature; for example, time-efficiency, cost-efficiency.

2) What properties effectively describe System Features?

a) Function: A resource-processing ability, which takes material, energy, or information resources as input, and uses a processing method and a recipe to create a material, energy, or information resources as output.

b) Interface: Means and conditions to access a system function, including key non-functional aspects.

3) What properties effectively describe Capabilities?

a) Behavior: Specification of state changes of some capability resources as a result of interactions with the external world (aligned with the function interface).

4) What properties effectively describe System Features enabling Business Features?

a) Root Cause: An ability that prevents a drawback or problem, or that enables a capacity of relevance to the business feature.

5) What properties effectively describe Capabilties enabling System Features?

a) Mechanism: A transformation of behavior to function, which may be thought of as constraints imposed on behaviors (i.e., behavior properties we wish to be satisfied under certain conditions) to achieve a desired effect.

B. Using the Enriching Road-mapping Concepts

With the enriching conceptual properties, we are now in a position to state specific new CQs that support non-ambiguous interpretation and collaboration, such as the following:

1) What Performances, influenced by the Business Feature, are of interest?

2) What Function, enabled by the System Feature, allows the Performance of interest?

3) What Behavior, enabled by the Capability, allows the target Function?

4) What is the Root Cause that the Function impacts, causing the Performance of interest?

5) What is the Mechanism imposed on the Behavior, which enables the Function of interest?

In this way, we added (1) new road-mapping concepts and relationships to increase precision and decrease ambiguity in communication within open innovation processes; and (2) new CQs that may be answered once the enriched concepts and relationships are defined for the innovation area at hand.

IV. USE CASE ILLUSTRATIONS

In this section, we illustrate how new conceptual properties may support formulation of and responses to new, specific CQs. We take two use cases from the NIST Smart Manufacturing R&D Program on Composable Apps. For each use case, we provide values for the properties of the enriched conceptual road-mapping model that give answers to new CQs.

A. Use Case 1: Efficient, Usable Messaging Standards Management Processes

Table 1 shows new conceptual properties for the first use case, driven by *Efficient, Usable Messaging Standards Management Processes,* which provide responses to new CQs.

TABLE I. BUSINESS FEATURE: EFFICIENT, USABLE MESSAGING STANDARDS MANAGEMENT PROCESSES

CONCEPT/ PROPERTY	VALUE
Business Feature	**Efficient, usable messaging standards management processes**
- Type	External
- Performance	Time-Efficiency, Usability
- *Root Cause*	Identification, reuse, and construction of messaging standards based on well-defined business context, supporting consistent interpretation
System Feature	**Messaging Standards Life Cycle Management (LCM) System**
- Function	Creates and maintains, throughout life-cycle, consistent, business-context-specific messaging standards specification
- Interface	Messaging Standards LCM System User Interface (UI)
- *Mechanism*	Business Process and Message Exchange shared model definition
Capability	**Business Process Model Variability Management Method (Algorithm)**
- Behavior	Common patterns-based variability management of Business Process Model (BPMs) based on explicit Business Process and Message Exchange context conceptualization

B. Use Case 2: Consistent, Repeatable Integration Processes

Table 2 shows new conceptual properties for the second use case, driven by *Consistent, Repeatable Integration Processes*, which provide responses to new CQs.

TABLE II. BUSINESS FEATURE: CONSISTENT, REPEATABLE INTEGRATION PROCESSES

CONCEPT/ PROPERTY	VALUE
Business Feature	**Consistent, repeatable integration processes**
- Type	Internal
- Performance	Time-Efficiency
- *Root Cause*	Sharing of the aspects of the process (methods, terminology, guidelines) among the partners, preventing interpretation conflicts
System Feature	**Architecture/methodology for developing and maintaining standard-based, service-oriented integrations**
- Function	Creates and manages modularity-supporting, encapsulation-enabling, expandable, well-behaved systems integration/engineering approaches/specifications
- Interface	Design guidelines, tools
- *Mechanism*	Shared context definition model/ontology
Capability	**Evolvable/adaptable taxonomies and information models**
- Behavior	Terminology and conceptualization definition that can adopt to real world situations by iterative evolution of such terminologies and concepts for shared context definition of systems integration

V. Discussion

It is worthwhile to analyze the previous use cases in terms of value types assigned to conceptual properties. Next, we identify opportunities for development of KTs (i.e., road-mapping meta-model and ontology development) to support precise, unambiguous communication.

1) Business Feature (BF) refers to a process either including or following the System Function activities. This presents an opportunity to clarify and relate various Business Features, if they reference same value type, such as process.

2) Performance may take on numerous values that enable functional, utility-based, and non-functional reasoning. The property may also be used to prioritize desired performances.

3) Types may be only External, Internal, or External-Internal. This provides an easy way to clarify and discriminate between market, enterprise, or combined drivers.

4) Root Cause (RC) is either a characteristic (e.g., *"Sharing of the aspects of the process"*) or enumeration (e.g., *"Identification, reuse, and construction of messaging standards"*) of activities within and/or after the System Function activities. This presents an opportunity to clarify and relate various RCs. In addition, RC includes a statement of either enabling a capacity (e.g., *"supporting consistent interpretation"*) or preventing an issue (e.g., *"preventing interpretation conflicts"*). Enumerations of such capacities and issues of interest provides additional basis for clarification, comparison, and consistent interpretation.

5) System Feature (SF) is a description of a higher-level capability or a reference to an existing and, possibly, proven, capable higher-level approach (e.g., *"service-oriented integration"*) that relates to and informs the SF Function. References to shared codification of such higher-level approaches, architectures, or capabilities present an opportunity for disambiguation of an SF.

6) Function is a description of key transformations (e.g., *"creates and manages"*) and desired output and its qualities (e.g., *"encapsulation-enabling, expandable systems integration specification"*) that relates to and elaborates the System Feature description (e.g., What are implications of service-oriented integration?) Such specification of output qualities relates to the Root Cause (e.g., *"encapsulation-enabling, expandable systems integration specification"* positively affects *"sharing of the aspects of the processes"*).

7) Mechanism relates the external world to the Capability's Behavior, which references System Functions components (i.e., inputs, outputs, controls, and mechanism) within some form of a shared model that contains references to the outside world. Mechanism focuses on transformational aspect of the relationship between the Function and Behavior.

8) Behavior implies structure and content that relates to some specification of states and their changes, which constitute behavior. For example, in the second use case, the use of common patterns imply such states and changes, as the patterns are instantiated to create business process models. In other words, the state space and operators of change applied to that space are implicit in the set of the patterns and their parameterization used in business process modeling.

In addition, Behavior specification may be seen as making use of casual relations that govern that Behavior and imposes constraints on the relations, leading to desired System Functions. Behavior can be represented using ICOM (input, controls, outputs, mechanism) components of an IDEF0 model of system functions [9]. In that way, Behavior assigns properties to Function components and spells out intended meaning behind the Behavior concept.

VI. Conclusions

Our objective for this paper was to lay a foundation for knowledge-based methods in support of establishing and sharing definition of key concepts for innovation processes.

The primary contributions of the paper include (1) an extension of existing road-mapping architecture with concepts motivated from the Function-Behavior research; (2) a presentation of this conceptual foundation allowing greater precision and alignment in interpretations; and (3) illustration of application of such conceptual basis by answering competency questions for use cases from a new R&D program.

Our next steps include (1) adding temporal concepts to the model, addressing the strategic, innovative and operational activities, per road-mapping frameworks; (2) development of a formal metamodel and ontology, enabling a tool development based on the enriched model; and (3) evaluation of the enriched model for on-going road-mapping efforts in R&D programs.

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Any mention of commercial products is for information only; it does not imply recommendation or endorsement by NIST.

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