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▶ **To cite this version:**

Hyun Ahn, Tai-Woo Chang. Measuring Similarity for Manufacturing Process Models. IFIP International Conference on Advances in Production Management Systems (APMS), Aug 2018, Seoul, South Korea. pp.223-231, 10.1007/978-3-319-99707-0_28 . hal-02177892

HAL Id: hal-02177892

https://inria.hal.science/hal-02177892

Submitted on 9 Jul 2019

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Measuring Similarity for Manufacturing Process Models

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Abstract. In manufacturing companies, it is vital to manage their manufacturing processes in order to ensure high quality of products and manufacturing consistency. Because so-called smart factories interconnect machines and acquire processing data, the business process management (BPM) approach can enrich the capability of manufacturing operation management. In this paper, we propose BPM-based similarity measures for manufacturing processes and apply them to the processes of a real factory. In addition to the structural similarity of the existing studies, we suggest a production-related operation similarity. Our contribution is considered on the assumption that a manufacturing company adopts the BPM approach and it operates a variety of manufacturing process models. The similarity measures enable the company to automatically search and reutilize models or parts of models within a repository of manufacturing process models.

Keywords: Manufacturing process, Business process management, Process similarity, BPMN.

1 Introduction

As the evolution of manufacturing systems has been progressed rapidly, manufacturing companies are able to effectively perform the product lifecycle management (PLM) that includes planning, designing, and manufacturing for their products. Nevertheless, it is still challenging for large-scale manufacturing companies to manage a vast array of their manufacturing processes. Although ICT technologies (e.g., computer-aided manufacturing) have been introduced to promote technical support to the manufacturing operation management (MOM), more comprehensive methodology should be adopted to fully support manufacturing-process-centric management activities.

The business process management (BPM) approach can be one of the promising solutions to tackle this hurdle. BPM aims to continually improve processes through automation of the BPM lifecycle that consists of modeling, execution, monitoring, and redesign through optimization. By applying this approach, manufacturing companies will benefit from well-defined methodologies, standards, and process-centric engineering practices for optimizing their manufacturing processes.

In this paper, we propose process similarity measures for manufacturers that adopt the BPM approach. To this end, we first describe the transformation from document-

based manufacturing process data into BPMN-compliant manufacturing process models. Then, we will describe the similarity measures with illustrative models designed with the basis of real manufacturing processes for thermocouple probe products.

2 BPMN-based Manufacturing Process Modeling

The Business Process Model and Notation (BPMN) is one of the most outstanding standards for modeling business processes. It has a rich set of element types that can fully represent the context of a business process. Moreover, this standard can be easily extended, and it has been applied to modeling problems in various domains.

Manufacturing companies conventionally possess manufacturing process charts and bill-of-materials (BOM) specifications to define and manage their manufacturing processes. In case of the Republic of Korea, the KSA 3002 standard [1], which is for manufacturing process chart standard, has been used in manufacturing industries. However, it provides only a set of graphical symbols, and there is no technical support for the modeling and automatic executions of manufacturing processes.

A BOM specification contains detailed information about the components (e.g., materials, parts, subassemblies and end products) of each needed to manufacture a particular product. However, it is not sufficient to understand a production flow of a manufacturing process. A manufacturing process consists of a set of manufacturing operations, which have precedence relationships with other preceding and/or successive operations. In this regard, we additionally exploit BOMO (Bill of Material Operations [2]) concept to define production-flow-oriented information of manufacturing process examples.

As shown in Table. 1, each operation (e.g., wire welding) consumes a set of components and produces an intermediate component or end product. The preceding operation information provides an execution ordering of the operations within a manufacturing process. Through these basic ingredients of manufacturing process data (process chart, BOM, and BOMO), we can organize structures for manufacturing processes.

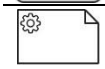
Table 1. BOMO data of the product examples

End Product	Operation		Component	Intermediate Component	Preceding Operation
	ID	name			
PROBE-01	OP6	Packaging	SUB-05, PACK-01, PACK-04, PACK-06, PACK-13, PACK-17	PROBE-01	OP5
	OP5	Insulation (cement)	SUB-04, MATL-11	SUB-05	OP4
	OP4	Housing	SUB-03, PART-08, PART-18, PART-19	SUB-04	OP3
	OP3	Wire injection	SUB-01, SUB-02	SUB-03	OP1, OP2
	OP2	Quartz tube winding	PART-15, MATL-02, MATL-04	SUB-02	-

	OP1	Wire welding	MATL-03, MATL-05, MATL-06	SUB-01	-
PROBE-02	OP6	Packaging	SUB-08, PACK-01, PACK-03, PACK-10, PACK-14, PACK-17	PROBE-02	OP5
	OP5	Insulation (cement)	SUB-07, MATL-09, MATL-10, MATL-13	SUB-08	OP4
	OP4	Housing	SUB-04, SUB-05, SUB-06, PART-02, PART-04, PART-18, PART-19	SUB-07	OP3, OP8, OP9
	OP3	Wire injection	SUB-01, SUB-02	SUB-04	OP1, OP2
	OP8	Bar welding	PART-09, PART-19	SUB-05	-
	OP9	Sealing	SUB-03, PACK-02, PACK-05	SUB-06	OP7
	OP7	Fastening	PART-10, MATL-01, MATL-07	SUB-03	-
	OP2	Quartz tube winding	PART-15, MATL-02, MATL-04	SUB-02	-
	OP1	Wire welding	MATL-05, MATL-06	SUB-01	-

To create process models for manufacturing processes, we apply the BPMN standard and extend its notations. The BPMN standard has a variety of its extensions, but there is a lack of modeling notations for the manufacturing domain. In spite of a few studies presented BPMN extensions for manufacturing processes [3], these extensions do not cover the whole context of the manufacturing domain due to the absence of uniformity. Accordingly, we define a minimal set of BPMN notations that suffices to model the examples we present in this paper.

Table 2. BPMN notations for manufacturing process models

Notation	Element type	Description
	Start event	A *Start event* indicates where a particular manufacturing process will start.
	End event	An *End event* indicates where a manufacturing process will terminate.
	Operation	An *Operation* is a generic term for manufacturing tasks. Each *Operation* can be performed by machines and/or human workers.
	Component	A *Component* is a generic term for raw materials, assemblies, and parts needed to manufacture a product.
	Parallel gateway	A *Parallel gateway* is used to create and synchronize disjunctive flows which proceed in parallel fashion.
	Sequence flow	A *Sequence flow* is used to show the order that operations will be performed in a manufacturing process.
	Component association	A *Component association* is used to link components (e.g., material, part) and operations.

Regarding the control-flow aspect, we limit the notations to focus on the examples including only sequential and parallel control-flow patterns. However, we need to add extra notations for other patterns, such as selective and repetitive patterns to facilitate modeling of sophisticated types of manufacturing processes and systems. Fig. 1 shows a modeling result of the examples. Both models represent the manufacturing processes for thermocouple products in the same category. In the next section, we will describe the overall procedure of measuring similarity by taking these models as an example.

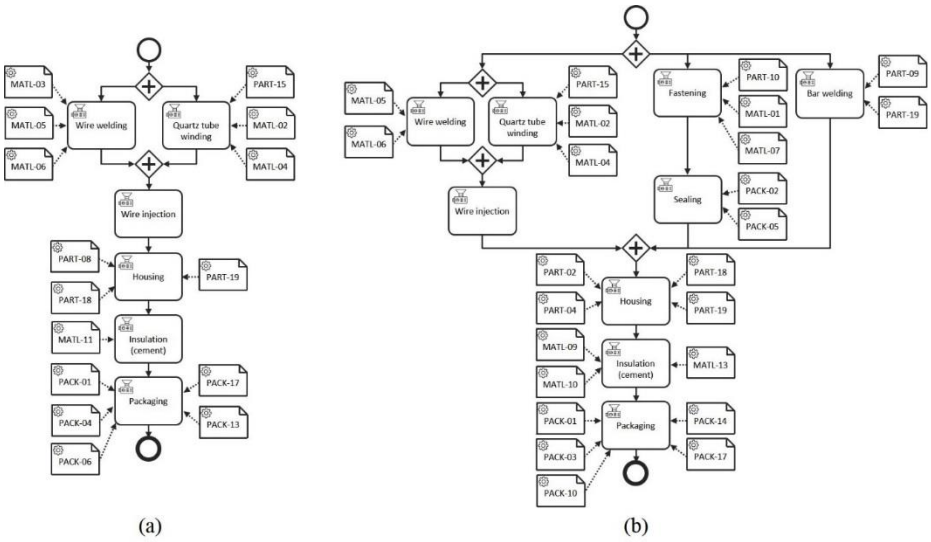


Fig. 1. Transformed BPMN manufacturing process models

3 Similarity Measure

Our measuring method of similarity encompasses two sub-concepts of similarity: operation similarity and structural similarity. In this section, we describe an operational procedure of the method with the example models of Fig. 1 to confirm the applicability of our method.

3.1 Preliminaries

We denote a set of manufacturing process models as $\mathbf{M} = M_1, \dots, M_n$ with n indicating the number of manufacturing process models, a set of operations as $\mathbf{OP} = OP_1, \dots, OP_m$ with m indicating the number of operations, and a set of components as $\mathbf{C} = C_1, \dots, C_l$ with l indicating the number of components. We also introduce a mapping function $\delta(\mathbf{OP}) \rightarrow \wp(\mathbf{C})$ that maps from an operation OP_k^i to input components of OP_k^i which are a subset of total components, where $OP_k^i \in \mathbf{OP}$ is the operation OP_k in the process model M_i.

3.2 Operation Similarity

Although many similarity concepts have been proposed for business processes, the manufacturing process has many features that distinguish it from the business process. In particular, production-related factors, which determine the characteristics of a manufacturing process, must be addressed in measuring similarities.

The operation similarity we introduce in this paper is a similarity concept based on associations between operations and components that is one of these influential factors. Mostly, each operation requires a group of certain components to produce end products or intermediary components. Based on this feature, we can calculate a similarity between operations of the same type in different processes. If two operations are the same type of operations but have associations with different component types, we consider two operations to have different characteristics. Mathematically, this similarity is based on the Jaccard coefficient, which is calculated by the division of the number of elements in the intersection set by the number of elements in the union set. Accordingly, the operation similarity between each operation OP_k in the process models M_i and M_j is calculated by Equation 1.

$$J\left(OP_k^i, OP_k^j\right) = \frac{\left|\delta\left(OP_k^i\right) \cap \delta\left(OP_k^j\right)\right|}{\left|\delta\left(OP_k^i\right) \cup \delta\left(OP_k^j\right)\right|} \tag{1}$$

For example, there are two *Housing* operations (in Fig. 2) of the same type that is included in two different process models M_1 and M_2. The *Housing* operation in M_1 (Fig. 2(a)) is associated with the set of input components $\delta(OP_4^1) = \{$PART-08, PART-18, PART-19$\}$, that is different from the set of input components of the *Housing* operation in M_2 (Fig. 2(b)), $\delta(OP_4^2) = \{$PART-02, PART-04, PART-18, PART-19$\}$. Accordingly, the operation similarity between these two operations is 2/5 = 0.4.

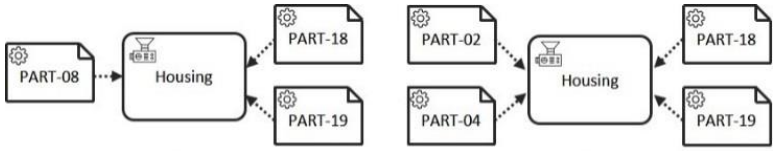


Fig. 2. Operation-component associations

In this regard, an operation similarity matrix including operation similarity measurements for all pairs of process models is defined as $X = (x_{rk}) \in \mathbb{R}^{\frac{n(n-1)}{2} \times m}$, where an element x_{rk} represents an operation similarity measure $J\left(OP_k^i, OP_k^j\right)$ between two operations of OP_k for the rth process model pair of the process models M_i and M_j.

Based on the above, the operation similarity matrix of the example equals to the row vector represented by $X = [0.67, 1, 0, 0.40, 0, 0.25, \ldots, 0]$ since the example contains only two process models. Operation similarity measurements affect the total similarity between two process models.

3.3 Structural Similarity

In this paper, we employ the similarity concepts of activity vector and transition vector similarities, both are presented in [5]. Accordingly, we redefine these similarity concepts to fit manufacturing process models and call them structural similarity.

The structural similarity has two parts: operation vector similarity and transition vector similarity, and these concepts are slightly different from the similarity concepts for business process models [5]. The total similarity is measured by putting these two similarities together.

Operation Vector Similarity. A manufacturing process comprises multiple operations that consume components and produce intermediate components or end products. Therefore, information indicating whether a specific operation is included in the process is the salient feature that characterizes manufacturing processes. An operation vector v_i^O is an m-dimensional vector, where each element $v_{k,i}^O$ is a binary value (0 or 1) representing whether the operation OP_k is included in the process model M_i.

$$v_i^O = \left[v_{1,i}^O, v_{2,i}^O, \dots, v_{m,i}^O\right] \tag{2}$$

The operation vector similarity $sim_{ov}(M_i, M_j)$ is measured based on the Cosine coefficient. Given two operation vectors corresponding to two different manufacturing process models respectively (M_i and M_j), the Cosine coefficient quantifies the similarity between these two vectors.

$$sim_{ov}(M_i, M_j) = \frac{\sum_{k=1}^{m} v_{k,i}^O \, v_{k,j}^O \, x_{rk}}{\sqrt{\sum_{k=1}^{m}\left(v_{k,i}^O\right)^2 \sum_{k=1}^{m}\left(v_{k,j}^O\right)^2}} \tag{3}$$

x_{rk} is an operation similarity measurements of OP_k between M_i and M_j and it is a part of the numerator in the above equation. It implies that even if these vectors equal to each other, according to the operation similarities, the operation vector similarity varies from 1 to 0. For our example, the measured operation vector similarity is $sim_{ov}(M_1, M_2) = \frac{3.32}{\sqrt{54}} \approx 0.45$.

Transition Vector Similarity. The transition is the fundamental property of all kinds of process models which is formally represented as a directed acyclic graph (DAG). The causality of tasks (or operations) in a process model is established based on transitions between the tasks, and it is a main structural property of process models including manufacturing processes. For example, the first task in a process model precedes to all other tasks including a succeeding task directly following to the start task. Therefore, causal relationships between tasks are quantified and weighted through calculations of distance weights, and these are represented as a transition vector.

Let v_i^T, be a transition vector of process model M_i. v_i^T is a row vector containing $m \times m$ elements for all pairs of operations, where each element $v_{kl,i}^T$ represents a

causal relationship between OP_k and OP_l, measured by the reverse of distance weight $d^T_{kl,i}$ between OP_k and OP_l.

$$v^T_i = \left[v^T_{11,i}, v^T_{12,i}, \dots, v^T_{mm,i}\right] \tag{4}$$

$$v^T_{kl,i} = \frac{1}{d^T_{kl,i}} \tag{5}$$

The Cosine coefficient-based transition vector similarity $sim_{tv}(M_i, M_j)$ is measured by the following equation.

$$sim_{tv}(M_i, M_j) = \frac{\sum^m_{k=1}\sum^m_{l=1} v^T_{kl,i} \cdot v^T_{kl,j}}{\sqrt{\sum^m_{k=1}\sum^m_{l=1}\left(v^T_{kl,i}\right)^2 \sum^m_{k=1}\sum^m_{l=1}\left(v^T_{kl,j}\right)^2}} \tag{6}$$

Based on the above equation, the result of measuring transition vector similarity between M_1 and M_2 for our example is $sim_{tv}(M_1, M_2) = \frac{6.45}{8.32} \approx 0.78$.

The total similarity between process models M_i and M_j is measured by putting these two vector similarities $sim_{ov}(M_i, M_j)$ and $sim_{tv}(M_i, M_j)$ together and adding a balancing parameter $\alpha \in [0,1]$ to blend them.

$$sim(M_i, M_j) = \alpha \cdot sim_{ov}(M_i, M_j) + (1 - \alpha) \cdot sim_{tv}(M_i, M_j) \tag{7}$$

For this example, the measured total similarity is $sim(M_1, M_2) \approx 0.62$ with the balancing parameter $\alpha = 0.5$.

4 Related Works

Many similarity measures have been suggested in the field of BPM to handle a large collection of process models. To support process design and modeling, different similarity measures have been proposed in order to find similar models and eventually to reuse and benchmark such models [4-6]. Searching process model [4,7] that satisfies specific conditions is another application of process similarity.

Despite a rich set of previous studies contributed to the process similarity, there is still a lack of proper methods for manufacturing processes since BPM approach has not been actively discussed in the manufacturing industry. As slightly different applications, the similarity concept was applied to the problems of machine groupings [8] for the design of manufacturing systems. Compared to our similarity, these studies presented similarity measures that focus on relations between machines and components and therefore such measures are not process-centric. Therefore, to the best of our knowledge, our work is first attempt to measure similarities between manufacturing process models. Particularly, our similarity takes into account the relationships between operations and components for quantifying similarity among operations of the same type.

Overall, we believe that our similarity is distinguished from the existing similarity concepts in both fields of BPM and manufacturing. However, the proposed similarity

should be more elaborate, possibly incorporating other factors that characterize manufacturing processes, such as production volume and operation time.

5 Conclusion

In this paper, we propose similarity measures for manufacturing processes, which are based on BPM approach. To facilitate the similarity measures, we presented the description of transformation from manufacturing data into BPMN process models. With the running example, we confirmed that our similarity measures are applicable to manufacturing process models. In conclusion, measuring similarities between manufacturing process models enables us to search and reuse models in the design of new manufacturing processes. We believe that our similarities provide an opportunity to aid various engineering issues such as clustering and re-engineering of manufacturing processes. As future works, we plan to conduct a case study that applied the BPM-based manufacturing process management and our approach to the manufacturing company.

Acknowledgement

This work was supported by the GRRC program of Gyeonggi province. (GRRCKGU2017-B01), Research on Industrial Big-Data Analytics for Intelligent Manufacturing].

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