On Optimizing Collaborative Manufacturing Processes in Virtual Factories

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ABSTRACT: *In today's global manufacturing markets, manufacturing processes need be flexibly adaptable and efficient due to changing business demands and tough cost pressure. To cope with this situation, concepts such as Virtual Factories can be beneficially applied to facilitate the collaboration between enterprises, especially small and medium-sized ones, and therewith to achieve higher degrees of flexibility. In this paper, we propose an approach for optimizing manufacturing processes in Virtual Factories, which are realized by our research project ADVENTURE. This way, we achieve interoperability among the collaborating enterprises as well as flexibly adaptable and efficient manufacturing processes.*

KEY WORDS: *Process Optimization, Virtual Factory, Collaboration, Interoperability.*

1. Introduction

In today's global manufacturing markets, enterprises and factories, respectively, especially small and medium-sized ones, are facing various challenges such as short product lifecycles, changing business environments, and tough cost pressure. In order to cope with these challenges and to stay competitive in such global markets, manufacturing processes need to be flexibly adaptable and efficient. For supporting flexible process adaptations, concepts such as *Virtual Factories* aiming at enhancing and facilitating the collaboration between factories can beneficially be implemented and realized. In Virtual Factories, multiple *real* factories work closely together for collaboratively producing and providing goods and services. Achieving interoperability among the collaborating partner factories thereby is key. Making use of the concept of Virtual Factories, (collaborative) manufacturing processes need to be optimized for achieving efficiency. In this respect, we propose an approach for optimizing the structure of manufacturing processes and the selection of partner factories such that predefined constraints on non-functional aspects – as, e.g., production and delivery time or Carbon Footprint (CO2) levels – are satisfied and production cost are minimized.

The rest of this work is organized as follows: in Section 2 we briefly present our research project *ADVENTURE* for achieving Virtual Factories. Our approach for optimizing collaborative processes in Virtual Factories is described in Section 3. Section 4 finally concludes the paper.

2. The research project ADVENTURE

ADVENTURE – ADaptive Virtual ENterprise manufacTURing Environment – focuses on creating a framework that aims at supporting and enhancing the collaboration especially of Small and Medium-sized enterprises (SME). This is primarily realized by integrating the Information and Communication (ICT) systems of the collaborating SMEs for achieving interoperability among them and by providing enhanced monitoring facilities for monitoring the whole (collaborative) supply chain. Building on concepts from the field of Service-oriented Computing, ADVENTURE enables the creation of manufacturing processes in a modular way. Steps and activities of such processes can be modelled based on required skills and technical requirements. They are further enriched with semantic annotations such that a matchmaking can be carried out automatedly to find matching partner factories that have previously provided semantically enriched descriptions of their manufacturing capabilities and services to the ADVENTURE platform. This way, the process of finding (from a functional perspective) *fitting* partners is significantly facilitated by ADVENTURE. If, for instance, an SME requires quickly adapting its manufacturing processes due to dynamically changing customer requirements, it can use ADVENTURE to model the adapted processes along with a specification of the needed skills and manufacturing capabilities that it cannot provide itself. Conducting the aforementioned matchmaking, ADVENTURE shows and proposes appropriate partner factories. For achieving interoperability with the identified partner factories, ADVENTURE offers means for integrating their ICT systems, as previously stated.

If multiple factories come into question for realizing certain steps of the manufacturing process, the SME can select between them according to its needs on non-functional aspects. A corresponding optimization approach is presented in Section 3.

3. Optimization approach

Having briefly introduced the project ADVENTURE in the previous section, this section focuses on the optimization approach proposed in the work at hand. It thereby consists of two parts. The first part addresses optimizing the selection of partner factories and their offered manufacturing services, respectively, whereas the second part focuses on optimizing the structure of the modelled manufacturing processes.

3.1. *Optimizing service selection*

As previously stated, it will be possible to select between partner factories and services, respectively, based on non-functional aspects such as delivery time, CO2, cost, etc., if multiple services exist that are equally appropriate to perform the different activities and accomplish corresponding tasks of a process. In fact, the problem of selecting services based on non-functional aspects is commonly known and referred to in the literature as *Service Selection Problem*[1] (SSP) (Strunk 10). Related work in this field can be mainly distinguished by the workflow patterns (Aalst et al, 2003) and structure elements, the corresponding approaches consider, and by the type of optimization, i.e., whether the approaches aim at computing an optimal, e.g., (Ardagna et al., 2007), or a heuristic solution, e.g., (Canfora et al, 2005).

For optimizing service selection, our proposed approach aims at finding an optimal solution to the SSP. It differs from and extends related work in this field by considering OR-blocks, i.e., OR-splits with corresponding OR-joins, in addition to sequences, XOR-/AND-blocks, and by accounting for interlaced as well as unstructured workflows, which as yet have not been considered by related approaches.

For modelling the SSP as optimization problem, aggregation functions for aggregating values of non-functional service aspects according to aforementioned workflow patterns and structures have been developed. Due to space restrictions, the interested reader is referred to our former work in (Schuller et al., 2011), (Schuller et al., 2012) for further details. Exemplarily, we provide corresponding aggregation functions in Table 1.

	Cost (c)	*Delivery Time (d)*	*Production Rate (r)*
Sequence	$\sum_{i\in I_s}\sum_{j\in J_i} c_{ij}x_{ij}$	$\sum_{i\in I_s}\sum_{j\in J_i} d_{ij}x_{ij}$	$\min_{i\in I_s}(\sum_{j\in J_i} r_{ij}x_{ij})$
AND-block	$\sum_{l\in L}\sum_{i\in I_l}\sum_{j\in J_i} c_{ij}x_{ij}$	$\max_{l\in L}\left(\sum_{i\in I_l}\sum_{j\in J_i} d_{ij}x_{ij}\right)$	$\min_{l\in L}\left(\min_{i\in I_l}\left(\sum_{j\in J_i} r_{ij}x_{ij}\right)\right)$
XOR-block	$\sum_{l\in L} p_l \sum_{i\in I_l}\sum_{j\in J_i} c_{ij}x_{ij}$	$\sum_{l\in L} p_l \sum_{i\in I_l}\sum_{j\in J_i} d_{ij}x_{ij}$	$\sum_{l\in L} p_l \cdot \min_{i\in I_l}\left(\sum_{j\in J_i} r_{ij}x_{ij}\right)$
OR-block	$\sum_{h\in H} p_h \sum_{l\in L^h}\sum_{i\in I_l}\sum_{j\in J_i} c_{ij}x_{ij}$	$\sum_{h\in H} p_h \max_{l\in L^h}\left(\sum_{i\in I_l}\sum_{j\in J_i} d_{ij}x_{ij}\right)$	$\sum_{h\in H} p_h \min_{l\in L^h}\left(\min_{i\in I_l}\left(\sum_{j\in J_i} r_{ij}x_{ij}\right)\right)$

Table 1. *Aggregation functions*

While the parameters *c*, *d*, and *r* refer to non-functional services aspects as indicated in Table 1, the variables *x* constitute decisions variables indicating whether a service *j* for process step *i* is selected or not. Recursively applying the mentioned

[1] The Service Selection Problem is also referred to as Service Composition Problem.

aggregation functions according to the considered manufacturing process enables specifying the optimization problem. If necessary, appropriate linearization techniques (cf. Schuller et al., 2011) will be applied for obtaining a *linear* optimization problem that can be solved optimally by applying (Mixed) Integer Linear Programming (ILP) (Beasley 96). This way, an optimal service selection can be achieved.

3.2. *Optimizing process structure*

In addition to optimizing the selection of matching partner factories and their offered manufacturing services, the optimization approach presented in the work at hand also includes an optimization of the process structure. Optimizing the process structure in addition to optimizing the service selection is not addressed at all by related work. Thus, the work at hand extends related work to this degree.

In order to enable process structure optimization, the *space* for possible structure optimizations has to be explicitly indicated and provided. In ADVENTURE, we use the *Complex gateway* to indicate alternative process structures. For instance, in the example workflow in Figure 1, the process steps (PS) one, two, and three, i.e., PS_1 PS_2, and PS_3, are arranged in different structural orderings at the three different branches within the Complex-split and -join (forming a Complex-block). The three branches thereby indicate different execution possibilities assuming that it is not allowed in this example to execute all process steps PS_1, PS_2, and PS_3 in parallel. Thus, either the first, or the second, or the third branch, constituting allowed structures, is the optimal one. These three possibilities form the *space* for process structure optimization.

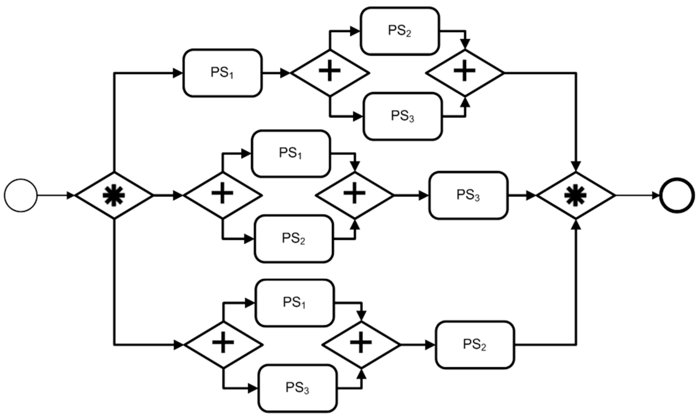

Figure 1: *Example workflow containing alternative structures*

In order to optimize the process structure, a selection of services has to be conducted since the optimal process structure depends on and is interwoven with the services selected for the corresponding tasks. As a first intuitive approach for optimizing the process structure in conjunction with selecting services, we propose to compute the optimal solution by considering each alternative branch separately for performing an optimal service selection step. For this, we adapt the aggregation functions by integrating a decision variable y indicating whether a certain branch k is considered as optimal regarding the process structure optimization or not. According to the example workflow in Figure 1, which contains a sequence and an AND-block within the Complex-block, the aggregation function for cost c is indicated in [1] – applying corresponding aggregation functions from Table 1.

$$\sum_{k\in K} y_k \left(\sum_{i\in I_{s_k}} \sum_{j\in J_i} c_{ij} x_{ij} + \sum_{l\in L_k} \sum_{i\in I_l} \sum_{j\in J_i} c_{ij} x_{ij} \right) \quad [1]$$

The aggregation functions for the other considered non-functional service aspects can be developed analogously. Accounting for the example workflow in Figure 1, the optimization problem is indicated in Model 1.

Model 1. *Optimization problem for example workflow*

$$\text{minimize} \quad \sum_{k\in K} y_k \left(\sum_{i\in I_{s_k}} \sum_{j\in J_i} c_{ij} x_{ij} + \sum_{l\in L_k} \sum_{i\in I_l} \sum_{j\in J_i} c_{ij} x_{ij} \right) \quad [2]$$

$$\sum_{k\in K} y_k \left(\sum_{i\in I_s} \sum_{j\in J_i} d_{ij} x_{ij} + \max_{l\in L} \left(\sum_{i\in I_l} \sum_{j\in J_i} d_{ij} x_{ij} \right) \right) \le b_d \quad [3]$$

$$\sum_{k\in K} y_k \left(\min_{i\in I_s} (\sum_{j\in J_i} r_{ij} x_{ij}) + \min_{l\in L} \left(\min_{i\in I_l} \left(\sum_{j\in J_i} r_{ij} x_{ij} \right) \right) \right) \ge b_r \quad [4]$$

$$\sum_{k\in K} y_k = 1 \quad [5]$$

$$y_k \in \{0,1\} \quad \forall k \in K \quad [6]$$

In [2], the objective function is provided, aiming at minimizing cost. The constraint in [3] restricts the delivery time to be lower or equal to a certain upper bound b_d while the constraint in [4] restricts the production rate to be larger or equal to a certain lower bound b_r. Both bounds need to be specified by the entity that is conducting the optimization. The constraint in [5] makes sure that only one of the possible process structures is selected, whereas [6] ensures that either a process structure is selected or not. Applying ILP, an optimal solution to the optimization problem in Model 1 can be computed. This way, both the process structure as well as the selection of services for the example workflow in Figure 1 may be optimized.

Having described the proposed optimization approach for optimizing manufacturing processes in this section, the subsequent Section 4 concludes the paper.

4. Conclusion and future work

In order to cope with the challenges in today's global manufacturing markets such as changing demands and tough cost pressure, we proposed an approach for optimizing manufacturing processes in Virtual Factories, which are realized by our research project ADVENTURE. This way, we achieve interoperability among the collaborating partners as well as flexibly adaptable and efficient manufacturing processes that are needed to survive in such global markets. In this respect, we extend related work by additionally accounting for process structure optimizations.

Due to space restrictions, no detailed evaluation results have been presented in this paper. However, since the number of potential process structures increases exponentially with the number of (non-parallel) Complex-blocks, the number of individual optimization problems to be solved – and therewith the computational effort – also increases exponentially. Thus, we will improve the concept for considering process structure optimizations in our future work and develop corresponding heuristics. Nevertheless, being able to compute the optimal solution as enabled by our approach is indispensable since the optimal solution constitutes the *benchmark* against which heuristic solution approaches need to measure themselves.

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