DynaMO: A framework to Optimize, Verify and Reconfigure Flexible Manufacturing Systems

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Abstract—**Industry 4.0 revolutionized the concept of manufacturing systems by introducing technologies such as Industrial Internet of Things (IIoT) sensors, collaborative robots, and flexible production lines. In such a context, timely response to unexpected events (*e.g.*, machine breakdown and production delays) is a fundamental requirement for enhancing the competitiveness of modern manufacturing.**

This thesis proposes a model-based framework titled Dynamic Manufacturing Orchestrator (DynaMO). The framework exploits data produced by the production plant and the knowledge embedded into models to optimize, verify and reconfigure manufacturing systems. By combining the knowledge embedded into models with the data produced from the production plant, the framework can be applied across different manufacturing contexts. The proposed framework has been prototyped to control a real production line, controlled by a commercial Manufacturing Execution System (MES), unable to fully exploit the flexibility provided by the case study manufacturing system. Meanwhile, the proposed framework is fully exploiting the production line's flexibility.

***Index Terms*—Manufacturing systems, Reconfiguration, Process modeling**

I. Introduction

The widespread introduction of information technologies in manufacturing enabled a wide set of new functionalities, making manufacturing systems more flexible. "Industry 4.0" [1] is meant to assist this transformation, proposing a set of *production systems development guidelines* to a wide range of engineering disciplines. Among the promises of the Industry 4.0 trend, *reconfigurability* stands out as a key factor to quickly adapt production to sudden market changes. To maximize the benefits of such a revolution, principles from the Service Oriented Architecture (SOA) paradigm have been introduced in manufacturing, generating the concept of Service Oriented Manufacturing (SOM) [2]. This paradigm assumes that the functionalities carried out by pieces of equipment are organized into "*machine services*" and exposing only the machine's interaction protocols by means of specific drivers [3].

In this new landscape, production recipes are implemented as a partially ordered sequence of machine services. This allows to increase the level of flexibility of such manufacturing systems by continuously adapting the production recipes with respect to sudden events, thus reducing their impact on the planned schedule. On the other hand, this degree of flexibility increases the complexity of such manufacturing systems, because the proposed methodologies must consider the impact

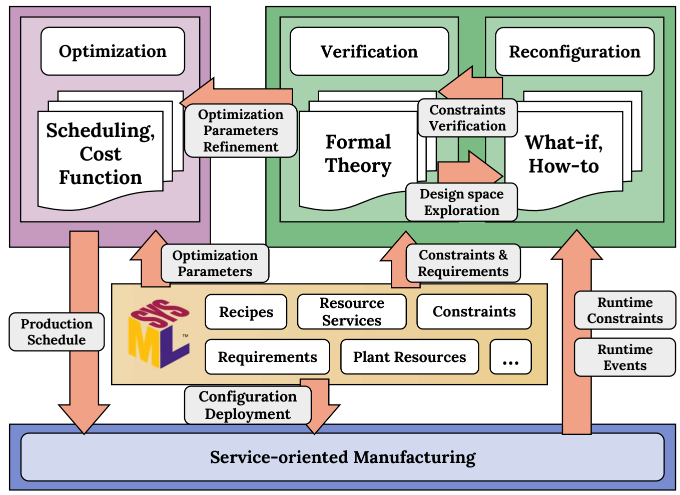

Fig. 1. Overview of the key components composing the proposed framework. 1) The interface with the manufacturing systems (lower part). 2) Model-based knowledge representation containing structure, functionalities, and requirements of the manufacturing system (center part). 3) Adaptive manufacturing processes manipulation based on optimization, verification, and reconfiguration (top part).

on the real world caused by machine services. Model-based knowledge representation is the key that allows to properly manage such complexity. It consists of modeling knowledge through modeling languages within models. In the past years, many different languages have been proposed to model different parts of manufacturing. For example, Business To Manufacturing Markup Language (B2MML), which is focused on modeling business processes, and Automation Markup Language (AutomationML), which allows modeling the topology, kinematics, and interaction with machines. Recent works [4], proposed System Modeling Language (SysML), as unified language to model manufacturing knowledge and also enabling models reuse. SysML provides an intuitive graphical language, explicitly tailored to express the structure and behavior of complex systems such as Cyber-Physical Production System (CPPS).

This thesis aims to fill the current gaps in the transition toward Industry 4.0, by proposing a framework titled DynaMO (depicted in Figure 1). The framework introduces and orchestrates a dynamic layer within the production plant, continuously adapting the manufacturing system to sudden changes. It consists of 3 main pillars: 1) A SOM architecture as the interface between the framework and the manufacturing systems (lower part of Figure 1); 2) Model-based knowledge representation (center part of Figure 1) consisting in the formalization of the manufacturing knowledge through models, ranging from information systems (*e.g.*, production recipes and plant topology) to the machines (*e.g.*, constraints, functionalities and machine behavior); 3) Adaptive manufacturing processes manipulation (top part of Figure 1), consisting of production schedule optimization, reconfiguration of production processes by evaluating *what-if* scenarios to learn *how-to* sequence and verification.

II. Achieved Results

To integrate new technologies and methodologies within manufacturing it is necessary to interact with also all the information systems that are already present. Therefore, to ease the integration and the development of these new technologies in [5] we proposed a SOM-ready software architecture called *Automation Manager*, which acts as a middleware between the production line and the MES. Furthermore, it automated the third level of the automation pyramid by implementing a dynamic scheduler, advanced data analysis, resource management, autonomous work order execution, and a module that enables communication with other custom components. It consists of three different layers and many sub-components; the first layer contains the *Driver* that manages the communication between machines and the MES; the second layer contains the *Core* components; the third layer contains the *Applications*, which implements custom functionalities.

In [6], we have proposed an automated approach to generate smart contracts for assessing production quality. The proposed methodology exploits SysML, to represent both the production recipe and the properties that must be verified (*e.g.*, KPIs).

Then, in [7] we proposed an extension of the classical representation such as Resource Task Networks (RTNs) and State Task Networks (STNs), that formalize production recipes as a directed graph, consisting of a hierarchical model for production processes. The model consists in three levels, each of them modeling a different abstraction of the production process.

- the *task level* consists of a task-resources graph. It allows describing the bones of the production process, which are the tasks, their dependencies and the machines on which such tasks can be allocated.
- The *service level* refines the concept of "task", describing the sequence of steps required to be carried out to complete the task.
- The *machine function level* describes the interactions that need to take place between the control software and the machine implementing a service as a directed graph.

In addition, in [7], we also proposed a reactive scheduling algorithm that exploits the knowledge represented within the three different abstraction levels of the proposed model. The algorithm takes advantage of the additional information to make a more precise decision on whether a process can be interrupted, interleaved, and preempted, thus improving the performance of the production systems. Then, in [8] we demonstrated the impact of correct estimation of tasks transport time in scheduling. We also proposed a heuristic based on randomization, which was able to find near-optimal schedules for task processing and transfer time between equipment in a few seconds. To detect when these scheduling algorithms must be executed in [9], we have proposed SMART-IC, a framework for smart monitoring and production optimization for semiconductor manufacturing that brings together anomaly detection, smart maintenance, and functional safety.

III. Thesis Completion

In the near future, I plan to improve and extend the proposed methodology by first extending the formalization of production recipes enabling requirements and constraints verification, and then developing a methodology in the loop able to explore *what-if* scenarios and learn from *how-to* sequence to reach a certain plant state. This will enable both the automatic generation and optimization of production recipes given a production line, and a final product to be produced. Furthermore, all these works will also be validated in the Industrial Computer Engineering (ICE) Laboratory: a research facility of the University of Verona[1], equipped with a fully-fledged production line (containing state-of-the-practice machines), governed by a commercial monolithic MES.

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