The automation and flexibility of production systems is a key step towards improved profitability and competitiveness in high labour cost areas, when producing high-complexity, low-volume products. In the Evolvable Assembly Systems (EAS) project, the ‘manufacturability’ (or ‘realisability’) and ‘control’ algorithms were introduced to accommodate the batch-size-of-one production of highly customisable products. These algorithms enable checking whether a production line can manufacture a given product with its available set of resources, and how the product should be manufactured, e.g. which resources to use, and when. To this end, the authors formally define production recipes, which represent products, and manufacturing resources which make up a manufacturing facility. This paper re-defines these notions in the ISO-standard EBNF (Extended Backus-Naur Form) notation, and adapts the manufacturability and control algorithms to accommodate the new definitions. The new algorithms and data structures reflect more closely the ones that are used in an implemented software tool. This paper also reports a method by which recipes and resources could be used to generate manufacturing process controllers in the Business to Manufacturing Markup Language (B2MML) standard. In doing so, this paper takes a step toward a complete path from the formal specification of a manufacturing facility and the products to be manufactured, to the automatic generation of executable process plans.

1. Introduction and Context

Advanced manufacturing is the result of the trend towards the integration of informatics with traditional manufacturing systems. These dynamic, adaptive, decentralised systems are used to manufacture product lines with a shorter time to market, increased product diversity, greater specialisation, and shorter lifecycles. A number of government-backed initiatives have arisen in recent years to support this trend, including the German Industrie 4.0 initiative[1,2], EU EFFRA Roadmap[3], US DMDII Strategic Plan[4], and the recent Japanese “Connected Manufacturing” Industrial Value Chain Initiative[5]. Academic research in the area includes reconfigurable manufacturing systems[6,7] with ‘plug and produce’ technologies[8,9], holonic manufacturing[10,11], organic computing[12], and the related evolvable production systems and evolvable assembly systems[8,13–15], among others.

The Evolvable Assembly Systems project at the University of Nottingham aims to investigate advanced manufacturing systems that are self-adaptive[16] and able to address the ‘batch-size-of-one’ problem, where each product to be assembled may be unique[15]. In[17], a formal approach was proposed to determine both whether a particular product is manufacturable given a set of available manufacturing resources (the manufacturability problem), and how the product should be manufactured using those resources (the control problem). Their approach takes as input the manufacturing resources, and the product in the form of a recipe specifying the operations necessary to manufacture the product, and produces a controller specifying the detailed steps to be executed by each manufacturing resource in the production line. In this paper the abstract representations of[17] are linked to concrete ISA-95 standards[18], and their algorithms are converted into a format that manipulates data structures that are defined using the standard ISO/IEC Extended BNF language[19], which also reflect more closely the data structures that are used in the actual implementation.

This paper first describes an example system in Section 2 which will serve as a running example in later sections. Section 3 defines production recipes and manufacturing resources in EBNF notation, which are used as input to the algorithms that check manufacturability and synthesise an abstract controller. Section 4 explains how a resulting abstract controller can be translated to a more suitable format for controlling industrial processes, and Section 5 provides the detailed algorithms for...
checking manufacturability and for synthesising an abstract controller. Section 6 summarises the paper.

2. Running Example

The Precision Assembly Demonstrator (PAD) [9] is based on the Modutech highly flexible assembly platform by Feintool. It consists of a shuttle transport system linking modular stations to a loading/unloading area; two KUKA six-axis robotic arms with associated workspaces; a shared tool changing rack; and a testing and inspection station. The modules and their layout is shown in Figure 1.

The parts to be assembled into a product are mounted on a pallet. At the loading/unloading area, the system operator can place the pallet on a shuttle that runs along a linear transfer system. In Figure 1, the six resources corresponding to the stations in the PAD are configured as follows: the pallet is first removed from the shuttle and placed at ‘Workspace 1’, a working area for ‘Robot Arm 1’, where the robot works on it before returning it to the shuttle; the ‘Tool-Changing Rack’ is shared between the two robot arms and holds a number of end effectors, including grippers and suction tools, that are used for product assembly; ‘Robot Arm 2’ and ‘Workspace 2’ are a mirror image of the previous robot and workspace, but otherwise identical; the ‘Testing Station’ allows vision and mechanical tests to be performed on the product once it has been assembled; the product is then returned to the loading/unloading area where an operator removes it from the system.

The product that is assembled with the PAD is a detent hinge for the cab interior of a truck. In the basic hinge, interior and exterior plastic leaves are fitted together and linked with a metal hinge pin. More complex hinges can be created by adding up to three metal ball–spring pairs within the interior leaf to adjust the engaging force. Additional end effectors may be used to apply glue to secure the hinge pin, or to engrave serial codes onto the leaves.

3. System Description

This section provides definitions for manufacturing resources which make up the manufacturing system, and for production recipes which represent products. These definitions are provided in the ISO/IEC Extended BNF language [19], and are based on the formal definitions in [17].

3.1. Resources and Topologies

In a manufacturing system, a (manufacturing) resource is a piece of hardware with a top-level controller (and possibly sub-controllers), which is typically a Programmable Logic Controller (PLC). The PLC controls the resource, sending signals to the hardware to perform actions, and collecting readings from sensors. Manufacturing resources are either production resources, which primarily perform observable operations on parts, or transport resources, such as a conveyor belt or shuttle system, which perform internal operations that transport parts between resources. Production resources can also perform internal operations, which would then enable operations such as data logging (e.g. from sensors), or maintenance actions.

Resources are defined as state diagrams, or more specifically, as labelled transition systems (LTSs), where nodes co-
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