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Design evaluation of automated manufacturing processes based on complexity of control logic

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Abstract

Complexity continues to be a challenge in manufacturing systems, resulting in ever-inflating costs, operational issues and increased lead times to product realisation. Assessing complexity realizes the reduction and management of complexity sources which contributes to lowering associated engineering costs and time, improves productivity and increases profitability. This paper proposes an approach for evaluating the design of automated manufacturing processes based on the structural complexity of the control logic. Six complexity indices are introduced and formulated: Coupling, Restrictiveness, Diameter, Branching, Centralization, and Uncertainty. An overall Logical Complexity Index (C_L) which combines all of these indices is developed and demonstrated using a simple pick and place automation process. The results indicate that the proposed approach can help design automation logics with the least complexity and compare alternatives that meet the requirements during initial design stages.

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Keywords: Process modelling; design efficiency; complexity indicator; complexity management.

1. Introduction

Manufacturing enterprises are challenged to constantly improve their production systems in terms of flexibility, reliability and responsiveness to satisfy customer demands for products with better features, unique functions and shorten product lifecycles [1]. To meet production targets of complex products with higher quality requirements and reduced time to market, the manufacturing industry is commissioning highly automated production systems, numerous sub-systems of various nature, including machining and processing systems, material handling devices and material storage and retrieval units [2] as well as more agile and responsive methods and strategies. According to ElMaraghy et al. [3], these changes have increased the complexity of manufacturing enterprises, all the way down to the shop floors.

An increase in complexity was reported to negatively impact all aspects of manufacturing, in terms of: production quality, reliability, throughput and production time at both operation, maintenance and organisational levels [3]. Although a significant number of academic studies have focused on analysing complexity of manufacturing processes and systems, there is still a crucial lack of understanding of both the nature and sources of complexity as well as the correlation between complexity and performance parameters, such as: productivity, flexibility and responsiveness [4]. A diagram summarizing the complexity issue within the manufacturing is illustrated in Figure 1.

Manufacturing processes become significantly complex as the product variety and the required functionality increase [5]. Complex automation processes are difficult to modify, change and maintain. In order to improve the quality of the automation processes, complexity should be minimized without losing the required functionality. In this paper, control logic of automated manufacturing processes is modelled as a component-based network in which a set of components cooperates together to achieve the common objective. A quantitative approach is proposed which produces measurable complexity indices based on the structural properties of the control logic. These indices are used to evaluate structural complexity of design alternatives and identify potential bottlenecks at an initial stage.

2. Literature review

Complexity phenomena in the manufacturing domain are becoming a popular research topic. In complex systems, small

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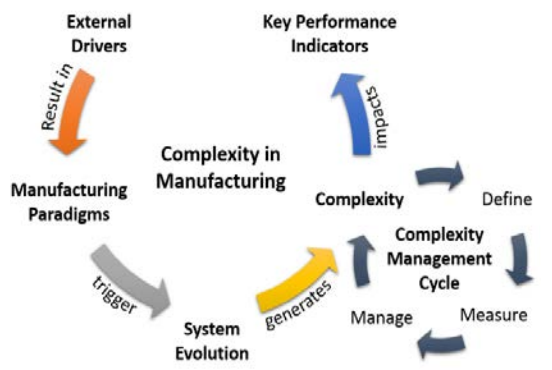

Fig. 1. Complexity in manufacturing domain

changes in initial conditions may lead to significant variations of the system's response, thus, complex systems may be very problematic to operate, control and maintain, and prediction of the behaviour of such systems are often impractical [2]. In the literature, complexity in manufacturing is defined within two domains: i.e. physical and functional [6]. Complexity in physical domain can be classified as static and dynamic [7]. Static (or structural) complexity represents internal and time independent characteristics of a system and focuses on interconnectivity between sub-systems or sub-modules [8]. The characterisation of dynamic (or operational) complexity focuses on operational characteristics of the system and its unpredictability over a time interval [9]. In a similar vein to the physical domain, Suh promoted an original approach to describe complexity in the functional domain, which can also be classified into two sub-groups, namely: time independent and time dependent [10]. According to this, complexity is used to represent emerged ambiguity while system is performing predetermined tasks under functional requirements.

In the last two decades, several approaches in measuring complexity of both manufacturing systems and processes have been offered. In this paper, approaches for complexity assessment have been categorized into four main groups (i.e. information theoretic measures, chaos and non-linear dynamics theory, heuristics/indices based metrics and hybrid measures). Information theoretic approaches offer an objective measure to identify and assess cause effect relationships. These measures have an ability to integrate systemic characteristics in a single measure and offer numerous advantages such as: adaptability to different types of systems, flexibility and ability to compare systems [11]. Nevertheless, information theoretic complexity measures can be seen as lack of, or insufficiently detailed practical methodology for applying into real case studies. Issues to be addressed include the impact of imperfect information, cost of the measurements, or conversion of the results into informative data and recommendations for generic and specific issues on system design and management.

Chaos theory provides a robust theoretical framework for understanding non-linearity, uncertainty and instability, and it is considered as a well-established science. However, some limitations bound back this approach. As highlighted in [12], existence of chaos in manufacturing has not been completely verified yet. In addition to this, manufacturing systems may exhibit stochastic events as well as chaotic behaviours. However, tools and methods developed based on theory of chaos and non-linear dynamics are not able to capture such events [13]. Furthermore, methods used for accurate estimation of the Lyapunov exponents require huge data sets and they are highly sensitive to variations in the input parameters [13].

Heuristic/indices based metrics are experience based methods which are used because of their effort saving characteristics when the true solution of a problem is impractical and/or time consuming to reach or converge. The heuristics based assessment approaches generally are used to find solutions for a specific focus or type of system (e.g. flexible manufacturing systems). These approaches can be considered a valuable tool to compare initial designs with possible alternatives. Although heuristics based measures are often used due to their ease of use, it is debatable as to whether these measures reflect overall system complexity accurately [3]. Also, the applicability of heuristics based approaches over different types of systems is often limited. Drawn from the limitations described above, a hybrid complexity model is proposed to assess structural complexity of automation control logics.

3. Modelling of an automation process control logic

In this paper, a method that combines finite state machines (FSM) and petri nets approaches, to model the control logic of automated manufacturing processes is introduced. In this approach, each automation field device has an abstract definition of its generic behavior represented by a state-transition diagram (STD) composed of constant number of states and transitions. These abstract definitions are not tied-in any specific application [14]. In STDs, states are connected to each other through transitions governed by sequence interlock conditions [15]. Instead of decomposing a given automation process from top to down, a process can be synthesised from bottom to up by designing STDs for individual system's components (e.g. sensors, actuators) and then connecting them in a way that enables them to cooperate and to achieve a common objective [16]. The connection between components is often called as interlocking or logically coupling the distributed STDs together to generate the system behaviours. In this approach, a system can be expressed mathematically as follows;

$$system = \{S, S_i, T, C\} \tag{1}$$

where: S is the set of all possible states in the STD, T is the set of all possible transitions in the STD, S_i is the initial state of each component's STD and C is the set of conditions that triggers the transitions. As an example, a STD describing the control behaviour of a simple feeding system control logic is given in Figure 2**.** This system includes three components. The feeder component can only exist in either one of two states ("*RETRACTED*" and "*EXTENDED*") connected by transitions ("*RETRACTING*" and "*EXTENDING*"). The directed black links represents the internal conditions. External conditions associated with a STD can be defined as the logical combinations (logical "AND" and "OR") of states of other