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Procedia CIRP 17 (2014) 278 – 283

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Variety Management in Manufacturing. Proceedings of the 47th CIRP Conference on Manufacturing Systems

Linking product and machine network structure using nested pattern analysis

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Abstract

The structure and variety of products that a company produces have a direct influence on the way a manufacturing system is designed. The implications of changes in the product variety or structure on the manufacturing system and resulting performance differences need to be considered by designers before introducing or changing products. In this paper, we suggest a measure derived from community ecology called "nestedness" to assess how changes in the product variety or structure can affect the operation-machine network of a manufacturing system in terms of its performance robustness. We define performance robustness as the manufacturing system's ability to keep a steady performance even in the face of disruptions such as product variety changes. We measure nestedness in an exemplary case study on a data set from a tool manufacturing job-shop and find the matrix of the network to be nested. The nested pattern means that there is a systematic relationship between operations and machines which results in performance robustness: if machines break-down, most other machines can be substituted. Similarly, if products are taken out from the portfolio, machines are still needed for the operations of other products. As such, our study is a first in examining the relationship between manufacturing system structure and performance robustness using interdisciplinary knowledge transfer with network science.

Keywords: nestedness, performance robustness, product variety, job-shop manufacturing

1. Introduction

Today's growing demand for product variety creates opportunities, such as expanding markets and increasing sales volumes, but also challenges for manufacturing companies [1]. It leads, for example, to an increase in manufacturing complexity [2], which can result in decreased manufacturing performance such as longer lead times, excess inventory [3], or increased vulnerability to fluctuations and disturbances. When increasing product variety, it should therefore be ensured that the performance of the manufacturing system (e.g., due date reliability, throughput time) and thus the customer service level are robust against changing product variety or structure.

Since products consist of several parts that are processed on the various machines in the manufacturing system, a change in product variety or product complexity has an influence on the structure of the network of machines. For example an increase in variety might mean that more specialized machines or more capacity are needed. A machine might gain more importance when product variety changes because it has to process more parts or is the only machine available for certain parts.

To consider these interdependencies between products and the manufacturing system before introducing new product variants, methods to depict the influence of product variety and structure changes on the machine network are necessary. It is especially important to analyze the influence of product variety changes on manufacturing performance (on key

doi:10.1016/j.procir.2014.01.089

performance indicators such as due-date reliability) to find out whether it behaves in a robust manner under changing product variety. If the system does not lose performance under changes, the system has performance robustness.

The general network of machines in a manufacturing system can easily be depicted as a graph, with machines as nodes and material flow between the nodes as links. This graph representation, which originates from complex network science, has in the past been increasingly applied to grouping or network analysis problems in manufacturing systems [4–6]. Similar to the network representation, the relations between the operations a part has to undertake and the machines that they are treated on can be depicted as a bipartite graph, in which the operations and machines are seen as nodes and an interaction between an operation and a machine is seen as a link. This creates a link between product structure and the manufacturing system, as the operations that are being processed on the machines are directly influenced when product variety changes.

In other scientific disciplines that are faced with large, complex systems (e.g., ecology), the analysis of such mutualistic networks often reverts to nested pattern analysis. In ecological systems, nested pattern analysis gives an indication of the relative stability of the system population [7] (i.e. one of the conditions of system robustness), and is used to gain insights into the dynamics or robustness of these otherwise difficult to analyze systems [8], [9]. It has recently also been applied to bipartite networks in other domains, such as organizational networks [10] and supply chains [11].

The aim of this paper is to use nested pattern analysis to analyze the operations and machine network in a manufacturing system and to suggest nestedness measures as adequate measures for performance robustness.

In the second section, we give a short overview on approaches that investigate the influence of product variety on different aspects of manufacturing system performance. The third section introduces the concept of nestedness in ecology, presents examples for its application in other scientific fields and discusses how we can confer it to manufacturing systems. In the fourth section, we investigate whether nested patterns are present in a real-case manufacturing system's operation-machine network. The conclusion briefly discusses how this measure can be linked to performance robustness.

2. Assessing the impact of product variety on manufacturing system performance

Is has been widely argued that product variety can have an influence on the manufacturing system performance and that the coupling between product variants and the manufacturing system should be thoroughly considered by manufacturing system designers [1,12]. To analyze the effect of product variety on manufacturing performance, MacDuffie et al [13] study a dataset of automotive manufacturers. They hypothesize that product variety (measured as model mix complexity, parts complexity, option content, and option variability) serves as a predictor of variability in performance (measured as total labor productivity and consumer-perceived product quality), which they test using a regression analysis. They show that parts complexity has a significant influence on manufacturing productivity.

A further study by Fisher & Ittner [14]enhanced the previous finding by a simulation model with which the effect of increased product variety on required labor was investigated. It was found that option variability has a greater negative impact on productivity than option content, but also that random variability has a much greater influence on required labor than option variability.

In [3], an analytical model is used to explore the effect of product variety (number of different products) on inventory costs (holding costs per unit and backordering costs per unit). The findings show that inventory costs increase linearly with the number of products. This is supported by another study which analyzes the impact of product variety (number of different products) on the performance (inventory costs, backorder costs) of a manufacturing system. With constant demand, the cost of inventories and backorders increases linearly with the number of products [15].

It is further shown by Wan et al [16] that increasing product variety (measured as the number of stock keeping units) raises the difficulty of managing inventory and reduces operational performance (measured as the unit fill rate), as it has a nonlinear impact on operational and sales performance.

Much of the existing research has been tackling the question of which performance metrics are influenced in which way by increasing product variety. However, few approaches have tried to assess the influence of increased product variety on the robustness of manufacturing performance (performance robustness), and only little attention is given to manufacturing operational performance metrics, such as due date reliability or throughput times.

3. Nestedness in ecological, real-world, and manufacturing systems

3.1. Nestedness as a system characteristic of ecological communities

Ecology is defined as "the study of organisms in relation to the surroundings in which they live" [17]. A long-standing area of study has been on the survival rate of species sharing the same habitats, with a special emphasis on species diversity and on how species interact and coexist [18]. A major issue within this field is the question of biological conservation, i.e. how and when do species go extinct and what the reasons for the inherent robustness against extinction in some ecosystems are [19,20].

In the course of analyzing species extinction in the Rocky Mountain area, a pattern in the distribution of different montane mammal species among the different mountain ranges, termed 'nested subset pattern', was identified [21]. A nested subset pattern means that the species that constitute a small fauna are proper subsets of the species that constitute richer faunas. This pattern was then shown to be also present in mammalian fauna on different island groups, where smaller islands contain only a proper subset of the species found on all larger islands [22]. This is schematically represented in Fig. 1, where a nested and a non-nested island group are