Arkadiusz Gola[1], Antoni Swic[2]

RECONFIGURABLE MANUFACTURING SYSTEMS AS A WAY OF LONG-TERM ECONOMIC CAPACITY MANAGEMENT

This article presents a new class of manufacturing systems which allow optimizing the capacities in the long run. When designing a production system, manufacturing engineers have to decide which type of the system and its configuration are the most suitable to produce the optimal number of products at the lowest costs.

Keywords: *economic efficiency; manufacturing processes optimization; system configuration; manufacturing system design.*

Аркадіуш Гола, Антоні Свіць

РЕКОНФІГУРОВАНІ ВИРОБНИЧІ СИСТЕМИ ЯК ЗАСІБ ДОВГОТРИВАЛОГО ЕКОНОМІЧНОГО УПРАВЛІННЯ ВИРОБНИЧИМИ ПОТУЖНОСТЯМИ

У статті представлено проблеми планування та управління виробничими потужностями, а також новий клас виробничих систем, який в довгостроковому плануванні дає можливість оптимізувати рівень потужностей виробництва. На етапі проектування виробничого процесу фахівці приймають важливе рішення щодо вибору найбільш відповідної форми виробничої системи та її конфігурації задля забезпечення виробництва оптимальної кількості високоякісної продукції за мінімальних витрат.

Ключові слова: *економічна ефективність; оптимізація виробничих процесів; конфігурація системи; проектування виробничих систем.*

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Аркадиуш Гола, Антони Свиц

РЕКОНФИГУРИРУЕМЫЕ ПРОИЗВОДСТВЕННЫЕ СИСТЕМЫ КАК СПОСОБ ДОЛГОСРОЧНОГО ЭКОНОМИЧЕСКОГО УПРАВЛЕНИЯ ПРОИЗВОДСТВЕННЫМИ МОЩНОСТЯМИ

В статье представлены проблемы планирования и управления производственными мощностями, а также новый класс производственных систем, обеспечивающий динамическую оптимизацию уровня производственных мощностей при долгосрочном планировании. На стадии проектирования системы инженеры принимают стратегическое решение, касающееся выбора наиболее подходящей формы производственной системы, а также ее конфигурации с целью обеспечения производства оптимального количества изделий надлежащего качества при минимальных затратах.

Ключевые слова: *экономическая эффективность; оптимизация производственных процессов; конфигурация системы; проектирование производственных систем.*

Introduction. Due to customer-driven economies, today's world markets are characterized by high fluctuations in market demand and frequent arrival of new technologies and new products. To stay competitive at such markets manufacturing companies require new types of manufacturing systems that are very responsive to global movements. A new cost-effective manufacturing system whose production capacity and/or functionality is adjustable in response to fluctuations in product demand, and which is designed to be upgradeable with new process technology needed to accommodate tighter product specifications (Asl and Ulsoy, 2003).

[1] Lublin University of Technology, Poland.
[2] Lublin University of Technology, Poland.

A manufacturing system is usually designed under a set of assumptions on the environment in which the company will operate (Swic et al., 2014). On the other hand, it often occurs that a production system must be expanded because of different reasons such as the increasing volumes requested by the market, or the arriving of a new product that has to be manufactured. In order to simplify the design phase of the system, most of configuration parameters (demand, product, costs etc.) are assumed to be constant or, in the best cases, variable in some defined ways (Anglani et al., 2000).

In this paper we analyze a new type of manufacturing system developed in the NSF Engineering Research Center and called Reconfigurable Manufacturing System from the capacity planning and expansion point of view. In particular we focus on the task of scalability which is an important system characteristic at markets subject to volatile demand.

Literature review. There is a vast amount of literature on optimal capacity investment and an extensive survey on the topic. An extensive survey on the topic of optimal capacity investment has been provided by (Van Mieghem, 2003). Several studies consider both initial investments and optimal capacity adjustments over time (Katz et al., 2002; Asl et al., 2003). However, as argued in (Dixit and Pindyck, 1994), continuous capacity adjustments may not be possible in many settings due to irreversibility. Therefore, investing in optimum quantities and types of capacity at the beginning of a planning horizon is crucial for profitability in the long run. There exist many works showing economic benefits of employing flexible systems. Particularly, Van Mieghem (1998) and Gola & Swic (2013) study optimal investment in dedicated and flexible capacities under uncertainty and show how several problem parameters including investment cost and demand uncertainties effect optimal investment decisions. Moreover, manufacturing capacity planning strategies were presented by (Ceryan and Koren, 2009).

On the other hand, many researchers propose models for manufacturing scalability management. Son, Yip-Hoi and Koren (2002) developed one of the first algorithm that addresses capacity scalability, but this early algorithm was limited to upgrading the capacity of serial lines only. A more comprehensive approach was presented in (Spicer et al., 2002) where scalability was analyzed as one of the critical issues in designing large, complex machining systems. Capacity scalability may be also achieved by scaling the capacity of individual pieces of equipment as presented in (Spicer et al., 2005; Youseffa and ElMaraghy, 2008; Zang et al., 2010). However the most practical approach to system scalability is adding or removing machines to or from existing manufacturing systems, and in this cases the original system layout design is critical for achieving cost-effective scalability (Arifara and Ismail, 2009). Moreover, optimization algorithm based on genetic algorithm for scalability planning for reconfigurable manufacturing systems was presented by (Wang and Koren, 2012). Finally, state-of-the-art and future developments roadmap in the area of scalability in manufacturing systems design and operation was presented by (Putnik et al., 2013).

Capacity management problem formulation. In this paper, we consider the task of optimal capacity investment decisions over a long-term planning horizon. This decision addresses two major issues: 1) how much capacity to build?; 2) whether to invest in dedicated or flexible systems, or a portfolio consisting of both dedicated and flexible systems? (Ceryan and Koren, 2009).

Let us consider a capacity management problem for a firm that produces only one type of goods over a finite N-unit time horizon under stochastic market demand as presented by (Asl and Ulsoy, 2003). It is assumed that no inventory of finished goods is allowed in this company. Capacity management is performed by observing the current capacity and the probability distribution of market demand at each time period, and making optimal decisions for the next period. Market demand is stochastic with independent distributions. It can be represented by a stochastic sequence of positive independent random variables D_k with apriori continuous cumulative probability distribution functions $\psi_k(D_k)$. The general structure of market demand is shown in Figure 1 where $\varphi_k(D_k)$ are the probability density functions of the stochastic demand process.

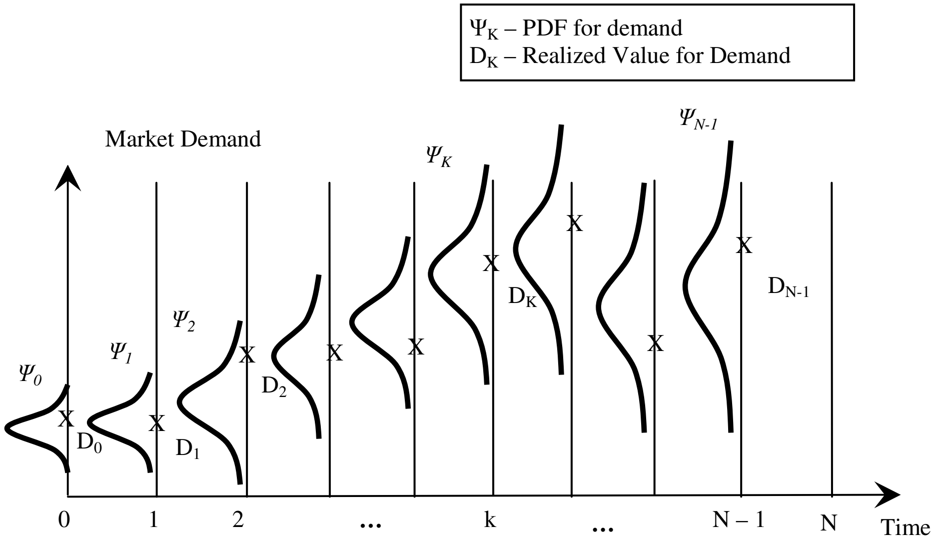

Figure 1. **Stochastic distributions of market demand** (Asl and Ulsoy, 2003)

Capacity management dynamics evolves in discrete time. It is assumed that there is a delay time from when the capacity is ordered until it can be used, shown by T. Dynamic capacity evolution is represented by:

$$y_k = \min(C_k, D_k); \quad (1)$$

$$C_{k+1} = C_k + X_{k-T}, \quad (2)$$

where C_k represents the capacity level of the firm at time k; X_k is the control input which defines the addition or removal of capacity; y_k represents firm's sales. The delay time T is limited to be a multiple of the time increment, k.

At each time k the decision maker observes the current capacity C_k and the demand distribution $\psi_k(D_k)$ and makes decision X_k, to generate the new optimal capacity level. The demand realization D_k is generated according to the given probability measure, and the operating cost G_k and control cost M_k are incurred and added to previous costs. The terminal cost is the additional cost, which incurs at time N and it will be added to previous costs. Assume that the firm operates at time $k + 1$, and it has a minimal or optimal cost-to-go $V_{k+1}(C_{k+1})$ which represents the cost of the optimal policy to go from time $k + 1$ to termal time N. Assuming the optimality of the cost-to-go function $V_{k+1}(C_{k+1})$, one can write the optimal cost-to-go function for the time k,

$$V_k(C_k) = \min_{x_k}\{M_k(X_k) + G_k(C_{k+1}) + \beta E V_{k+1}(C_{k+1})\}; \quad (3)$$

$$V_N(C_N) = -\gamma_N C_N, \quad (4)$$

where $V_N(C_N)$ represents the final salvage value of the company's capacity at time N. Equations (3) and (4) are the optimality equations for capacity management problem represented by stochastic dynamic programming. Based on the optimality theorem (Rocklin and Kasper, 1984), a Markov policy exists and is optimal and only if the minimum at (3) is achieved. To obtain the minimum value, it is shown that the optimal cost-to-go $V_k(C_k)$ is convex in C_k and the functions X_k, which make it minimal for $k = 0, 1, 2, ..., N - 1$ are obtained.

Manufacturing systems challenges and evolution. Manufacturing of the current century is a networking information world – inside and outside enterprises and lined to all market participants. Therefore, manufacturing systems had to face market constraints. Particularly, manufacturing systems have evolved to the form of job shops, which feature general-purpose machines, low volume, high variety and significant human involvement, to high volume, low variety and significant human involvement, to high volume low variety dedicated manufacturing lines (DML) driven by the economy of scale.

In the 1980s the concept of flexible manufacturing was introduced in response to the need for mass customization and for greater responsiveness to changes in products, production technology and markets. Flexible manufacturing systems (FMSs) were also developed to address mid-volume, mid-variety production needs (Gola et al., 2011). Similarities between parts in design and/or manufacture were used. Flexible manufacturing systems anticipated these variations and built-in flexibility a priori; hence they are more robust but have high initial capital investment cost. Flexibility and capacity attributes are sometimes under-used. In the 1990s, optimality, agility, waste reduction, quality, and lean manufacturing were the key drivers and goals for ensuring survival in a globally competitive market (Wiendahl et al., 2007).

Most manufacturing industries now use a portfolio of dedicated and flexible manufacturing systems to produce their products (Koren et al., 1999):

- *Dedicated manufacturing lines (DML)* or transfer lines, are based on inexpensive fixed autormation and produce a company's core products or parts at high volumes. Each dedicated line is typically designed to produce a single parte (i.e., the line is rigid) at high production rate achieved by the operation of several tools simultaneously in matching stations (called "gang drilling"). When product demand is high, the cost per part is relatively low. DMLs are cost effective as long as demand exceeds supply and they can operate at their full capacity. But with increasing pressure from global competition and over-capacity worldwide, there may be situations in which dedicated lines do not operate at their full capacity.

- *Flexible manufacturing systems (FMS)* can produce a variety of products, with changeable volumes and mix, on the same system. FMSs consist of expensive, general-purpose computer numerically controlled (CNC) machines and other programmable automation. Because of the single-tool operation of CNC machines, the FMS throughput is lower than DML. The combination of high equipment cost and low throughput makes the cost per part relatively high. Therefore, FMS production capacity is usually lower than that of dedicated lines and their initial cost is higher.

RMS – a new class of manufacturing system. Because of increasingly frequent and unpredictable market changes driven by global competition, including rapid introduction of new products and constantly varying product demand, manufacturing process at DMLs and FMSs is often not cost and market effective because of the under- or over-capacity of the system. To remain competitive, companies must design manufacturing systems that not only produce high-quality products at low costs, but also allow for rapid response to market changes and customer needs. Therefore in the mid-1990s, in the University of Michigan was developed the concept of reconfigurable manufacturing system (RMS).

RMS has been defined as "designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements" (Koren et al., 1999).

Reconfigurable manufacturing systems are marked by 6 core reconfigurable characteristic as summarized below (Koren and Ulsoy, 2002):

- *Customization* (flexibility limited to part family) – system or machine flexibility limited to a single product family, thereby obtaining customized flexibility.
- *Convertibility* (design for functionality changes) – the ability to easily transform the functionality of the existing systems and machines to suit new production requirements.
- *Scalability* (design for capacity changes) – the ability to easily modify production capacity by adding or subtracting manufacturing resources (e.g., machines) and/or changing components of the system.
- *Modularity* – compartmentalization of operational functions into units that can be manipulated between alternate production schemes for optimal arrangement.
- *Integrability* (interfaces for rapid integration) – the ability to integrate modules rapidly and precisely by a set of mechanical, informational, and control interfaces that facilitate integration and communication.
- *Diagnosability* (design for easy diagnostics) – the ability to automatically read the current state of a system to detect and diagnose the root causes of output product defects, and quickly correct operational defects.

The components of RMS are CNC machines, reconfigurable machine tools, reconfigurable inspection machines and material transport systems (such as gantries and conveyors) that connect the machines to form the system (Figure 2). Different arrangements and configurations of these machines have impact on system productivity. A collection of mathematical tools, which are the RMS Science Base, may be used to maximize system productivity with the smallest possible number of machines.

As summarized in Table 1, because of their key features reconfigurable manufacturing systems constitute a new class of systems characterized by adjustable structure and design focus.

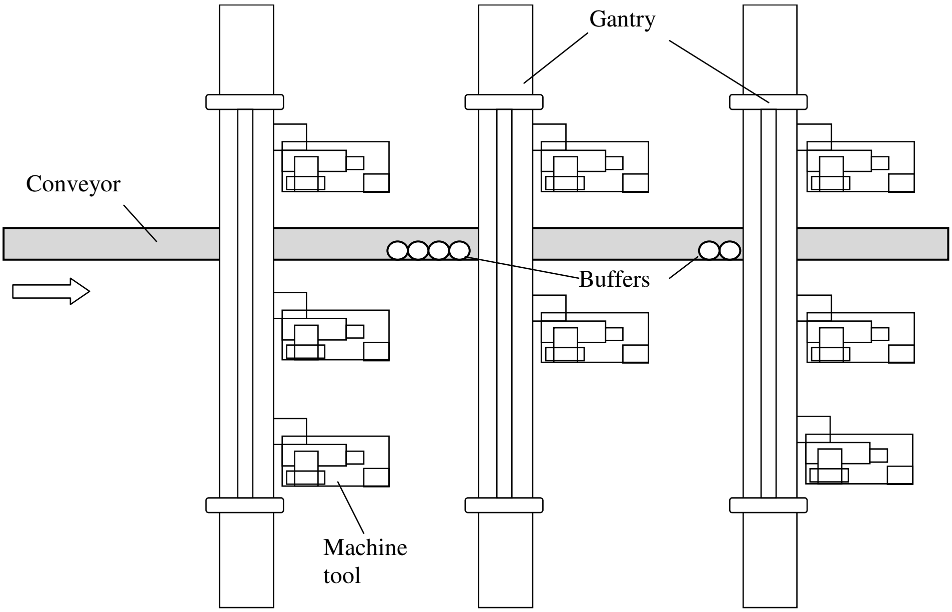

Figure 2. **Schematic layout of a RMS** (Wang and Koren, 2012)

Table 1. **RMS systems combine features of dedicated and flexible systems** (Koren and Shpitalni, 2010)

	DML	FMS	RMS
System structure	Fixed	Changeable	Changeable
Machine structure	Fixed	Fixed	Changeable
System focus	Part	Machine	Part family
Scalability	No	Yes	Yes
Flexibility	No	General	Customized (around a part family)
Simultaneously operating tools	Yes	No	Possible
Productivity	Very high	Low	High
Cost per part	Low (for a single part, when fully utilized)	Reasonable (several parts simultaneously)	Medium (parts at variable demand)

The 3 features – capacity, functionality and cost – are what differentiate 3 types of manufacturing systems. While DML and FMS are usually fixed at the capacity-functionality plane, RMS are not constrained by capacity or by functionality and are capable of changing over time in response to market circumstances (Figure 3).

Conclusions and further studies perspectives. Increased competition, globalization of markets are but a few of many challenges that manufacturing is facing currently. Companies today generally face two dilemmas regarding products and production design: the dichotomy between scale and scope on the one hand and the dichotomy between high plan and high value-orientation on the other. In order to stay competitive, companies should optimize their production systems along the continuum of both dichotomies.

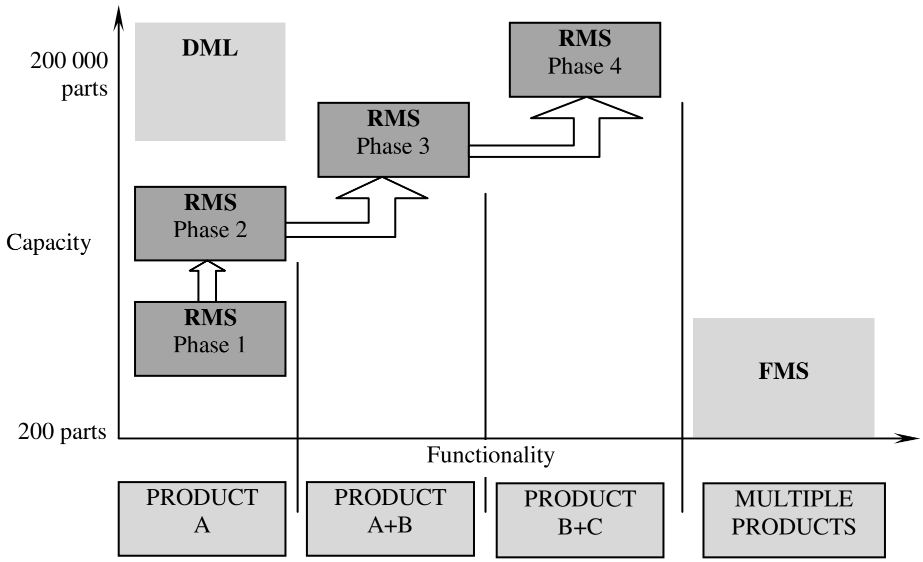

Figure 3. **Capacity and functionality of DML, FMS and RMS**

One of the most frequent problem is under- or over-capacity of the actually existing manufacturing systems which makes production cost and market effective. System production capacity must be adjusted to cope with fluctuations in product demand in the long term. This type of adjustment requires rapid changes in the system's production capacity.

This article presents a new class of manufacturing system developed in the NSF Engineering Research Center (Michigan, USA) from the capacity planning and expansion point of view. Assumptions of the system give hope the system will be able to achieve requirements of nowadays, global market. Unfortunately, in spite of the research provided for several years, RMS has been still only a theoretical concept and there are only several prototypes of it. Therefore, it is necessary to provide further research, also in the aspect of system's scalability. Further research should answer the following open questions:

- What are the appropriate models to describe system's changeability and scalability?
- It is possible to define an optimal mathematical model of system's scalability?
- Which production planning and control methods are suitable for scalable manufacturing systems?
- How can the change process itself be planned and performed with an appropriate speed and effort?
- How can quality be managed within frequently changing manufacturing facilities and global supply chains?
- What is the impact of scalability on feasibility and economic investment justification?

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