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ECONOMIC ASPECTS OF MANUFACTURING SYSTEMS DESIGN

The paper covers main economic aspects to be taken into account in the process of manufacturing systems design. In particular, the problems of manufacturing system selection, capacity planning, system configuration and their impact on financial and operational effectiveness of the system are presented in article.

Keywords: *manufacturing system; life cycle; flexibility; system configuration.*

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ЕКОНОМІЧНІ АСПЕКТИ ПРОЕКТУВАННЯ ВИРОБНИЧИХ СИСТЕМ

У статті представлено головні економічні аспекти, які слід враховувати в процесі проектування виробничої системи. Зокрема, висвітлено проблематику економічності при виборі системи, плануванні рівня виробничих потужностей, конфігурації системи, а також виявлено їх вплив на фінансову та економічну ефективність системи.

Ключові слова: *виробнича система; життєвий цикл; еластичність; конфігурація системи.*

Табл. 3. Рис. 2. Форм. 8. Літ. 22.

Аркадиуш Гола

ЭКОНОМИЧЕСКИЕ АСПЕКТЫ ПРОЕКТИРОВАНИЯ ПРОИЗВОДСТВЕННЫХ СИСТЕМ

В статье представлены ключевые экономические аспекты, которые необходимо учитывать в процессе проектирования производственной системы. В частности, определена проблематика экономичности выбора системы, планирования уровня производственных мощностей, конфигурации системы, а также показано их влияние на ее финансовую и экономическую эффективность.

Ключевые слова: *производственная система; жизненный цикл; гибкость; конфигурация системы.*

Introduction

Manufacturers today face more challenges than ever before due to highly volatile markets, which create large fluctuations in products demand. To remain competitive, companies must design manufacturing systems that not only produce high-quality products at low cost, but also face market changes in an economical way (Wang, Koren, 2012; Plecka et al., 2013). The cost of building a new manufacturing system may be between 50 mln to over 2 bln USD (a microprocessor fabrication facility), and its average lifetime is 12–15 years (Koren, 2010). Therefore, making an investment decision on a new manufacturing systems requires knowledge in engineering as well as finance and economics. Particularly, manufacturing system's planning includes a sequence of important decisions as follows:

1. Decide whether to invest at all in a new production system, and, if to invest, in which type of a system.
2. Based on product sale forecasting and estimated capital investment, to determine whether to invest in dedicated, flexible, or portfolio capacity.

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3. To calculate the cycle time of each operation and the total time needed for the whole process to produce one product.

4. Optimize the system configuration in such a way that a proper line balancing maximizes system throughput, and tooling cost is minimized to reduce capital investments.

5. Find out the buffer capacity that optimizes the system throughput.

6. Determine the projected operations costs; it is more challenging when flexible systems that produce several products are employed.

7. Consider system responsiveness to changing orders of customers; responsiveness impacts the system throughput.

8. Calculate the optimal speed of each machine; it will impact the whole system throughput.

Designing a system is not a sequential process that follows the above mentioned steps but is an iterative process that iterates among the above listed points until converging gradually to the optimal economic solution. For example, the system configuration affects tooling costs, which, in turn, effect capital costs, but the latter is needed to determine the system type. Moreover, the system operations cost impacts profit, and may change decisions on the total installed capacity.

In this article we focus on the economic aspects to be taken into account in the process of manufacturing systems design. In particular, the problems of manufacturing system selection as a function of products life cycle, capacity planning, system configuration and their impact on the financial and operational effectiveness of the system are presented.

Literature review

The problem of manufacturing systems design was studied by many researchers during the last decades and it is still under wide interest of scientific research. Many works present metrological solutions in the area of dedicated manufacturing lines (Chryssolouris, 2006; Brzezinski, 2013), flexible manufacturing systems (Tolio, 2009; Swic et al., 2011; Gola at al.; 2013) and also reconfigurable manufacturing systems (Bi et al., 2008; Koren et al., 2010).

In particular, research related to the problem of systems' capacity planning, scalability planning and configuration of the system were provided. An extensive survey on the topic of optimal capacity investment is provided in (Van Mieghem, 2003). Several studies consider both initial investments and optimal capacity adjustments over time (Katz et al., 2002; Asl et al., 2003). Van Mieghem studies optimal investment in dedicated and flexible capacities under uncertainty and shows how several problem parameters including investment cost and demand uncertainties affect optimal investment decisions (Van Mieghem, 1998).

Researchers at the NSF Engineering Research Center for reconfigurable manufacturing system developed one of the first algorithm that address capacity scalability (Son et al., 2001). A more comprehensive approach was presented by (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 (Youssefa et al., 2008), but 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 (Ariafara et al., 2009). A scalability planning methodology for reconfigurable manufacturing systems that can incrementally scale the system capacity by reconfiguring an existing system was presented in (Wang et al., 2012).

Determining the manufacturing system type from the economic viewpoint

Money used for building a new manufacturing system should earn returns for the invested capital. For a new manufacturing system to be economically viable, the projected sales of the products that the system will produce during its lifetime must be higher than the cost of the capital invested in building the system. The first decision task is often to choose the type of the manufacturing system.

In the example below we show how to use the net present value parameter (NPV) to evaluate life-cycle investments in dedicated manufacturing line (DML) and flexible manufacturing system (FMS) when producing 3 different products. By using simple economic model presented in (Koren, 2000), we study the effects of product life cycle and equipment reusability of each production system on the investment strategy for manufacturing firm.

Let's consider manufacturing to fulfill the demand of 3 different parts (Product A, Product B and Product C) where product generations for each product are the same and will be concerned in different life cycles from 1 to 12 years.

The demand volume is assumed to be 160000 for Product A, 110000 for product B and 80000 for product C per year, and the profit per part is respectively 110, 80 and 100 USD. The manufacturer may invest in either DML, or FMS. The DML costs 80 mln USD, and that of FMS is 115 mln USD. Once the next product generation arrives the same FMS can be reused, but there is a need for new fixtures, new tools, and ramp-up that cost 18 mln USD. At the end of its lifetime (12 years), the salvage value of the FMS (selling used CNC machining centers) is 40 mln USD. Each time a new product generation is manufactured a new DML must be built, but certain parts of the existing DML, worth 15 mln USD, can be either reused for a new line, or sold (have a salvage value). The annual interest rate is 9%.

Table 1 presents the cash flow forecast and PV of using DML and FMS for products generation in 5 years. As we can see the NPV value for the FMS (118,7) is little greater than for DML (102,0), so building FMS is more economical.

Table 1. **Cash flow (in mln USD) and net present value for DML and FMS for product life cycle of 5 years**

		Year	0	1	2	3	4	5	6	7	8	9	10	11	12
DML	Cash Flow	System	-80					-65					-65		15
		Prod. A		17,6	17,6	17,6	17,6	17,6	17,6	17,6	17,6	17,6	17,6	17,6	17,6
		Prod.B		8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8
		Prod.C		8	8	8	8	8	8	8	8	8	8	8	8
		Total	-80	34,4	34,4	34,4	34,4	-30,6	34,4	34,4	34,4	34,4	-12,9	34,4	49,4
		PV	-80	31,6	29,0	26,6	24,4	-19,9	20,5	18,8	17,3	15,8	-4,5	13,3	17,6
FMS	Cash Flow	System	-115					-25					-25		40
		Prod. A		17,6	17,6	17,6	17,6	17,6	17,6	17,6	17,6	17,6	17,6	17,6	17,6
		Prod. B		8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8
		Prod. C		8	8	8	8	8	8	8	8	8	8	8	8
		Total	-115	34,4	34,4	34,4	34,4	9,4	34,4	34,4	34,4	34,4	9,4	34,4	74,4
		PV	-115	31,6	29,0	26,6	24,4	6,1	20,5	18,8	17,3	15,8	4,0	13,3	26,5

NPV (DML) = 102,0; NPV (FMS) = 118,7

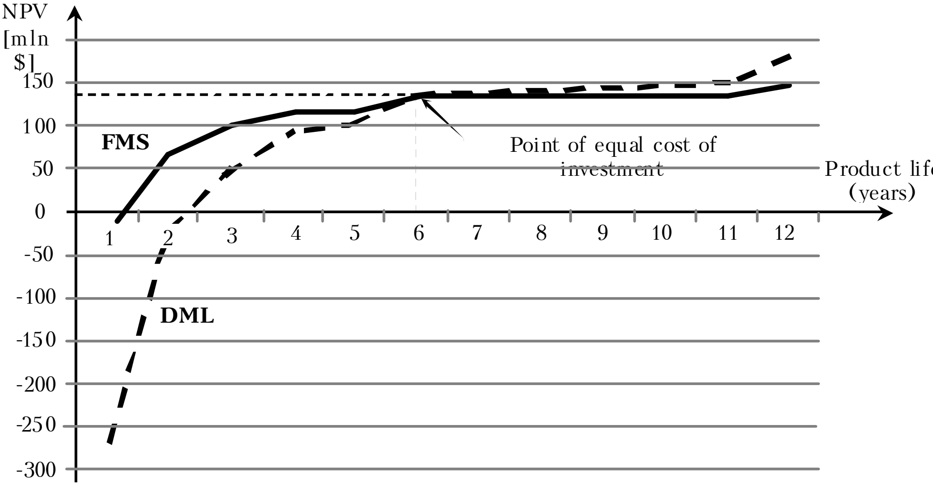
Source: Calculated by the author.

Now let us examine the case for different products lifetimes – from 1 to 12 years. The results of the obtained NPV are shown in Table 2. Figure 1 shows the NPV comparison between the two systems.

Table 2. **NPV for product life cycle from 1 to 12 years**

Product life cycle	1	2	3	4	5	6	7	8	9	10	11	12
DML	-271	-27,9	52,78	92,99	102,0	132,9	136,1	139,0	141,7	144,2	146,5	171,7
FMS	-24,6	68,78	99,83	115,3	118,7	130,6	131,9	133,0	134,0	135,0	135,9	145,6

Source: Calculated by the author.



Source: Developed by the author.

Figure 1. **An economic comparison of two systems: DML and FMS**

When analyzing the obtained results it is possible to draw the following conclusions:

1. If the expected products lifetime is less than 2 years, building FMS is a loss.
2. If the expected products lifetime is more than 6 years, install a dedicated machining line.
3. If the expected products lifetime is 6 years or less, install FMS.

Although these conclusions are drawn for a particular example, they may be considered as general rules for system life cycle economic planning.

Manufacturing capacity planning strategies

Beside the task of selection the type of manufacturing system, the optimal investment in the system capacity is a major decision to make. As defined in (Abele et al., 2006), flexible capacities "possess the ability to change over to produce a set of products very economically and quickly". Therefore, flexible systems may alleviate unfavorable effects of demand uncertainties. However, the versatility to produce multiple products often requires higher investment costs compared to dedicated systems that can only produce one type of products (ElMaraghy et al., 2009; Swic et al., 2013).

The problem of capacity planning must be sold in two stages. First, assuming that strategic investment decision is already given, we compute the maximum possible operating revenue during the entire lifetime of all products (i.e., the planning horizon). Next, we make the strategic capacity decision by choosing the recommended installed capacities that will generate the maximum profit that is corresponding to the highest operating revenue minus investment costs (Van Mieghem, 1998).

The problem may be formulated as a linear program with an optimization cost index (Koren, 2000). Cost index $\psi(d,k)$ expresses the revenue that can be achieved for a given capacity investment decision k, and for any fulfillment of product demands d over the planning horizon.

$$\Psi(d,k)=\max_{x,y}\sum_{t=1}^{T}\beta^{t-1}[p_A(x_A^t+y_A^t)+p_B(x_B^t+y_B^t)] \quad (1)$$

subject to constraints:

$$x_A^t \le k_A \quad \forall t=1,\ldots,T \quad (2)$$

$$x_B^t \le k_B \quad \forall t=1,\ldots,T \quad (3)$$

$$y_A^t + y_B^t \le k_{AB} \quad \forall t=1,\ldots,T \quad (4)$$

$$x_A^t + y_A^t \le d_A^t \quad \forall t=1,\ldots,T \quad (5)$$

$$x_B^t + y_B^t \le d_B^t \quad \forall t=1,\ldots,T \quad (6)$$

The decision variables x_A^t and x_B^t denote, respectively, how many units of dedicated capacity A and B are needed to fill the period t demand, whereas the decision variables y_A^t and y_B^t denote the optimal allocation of the flexible capacity between products. In addition, β is the discount factor per period that is used to calculate the NPV of the revenues, $\beta = 1/(1 + r)$, where r is the annual rate of return. Constraints (2)–(6) guarantee that one will assign neither more capacity than the maximum available, nor more capacity than demand (i.e., production quantities within a period do not exceed the available capacity and are bound by demand).

Having obtained the maximum operating revenue, it is possible now to write the strategic decision problem of determining the optimal capacity investments k.

$$\max_{k} \; E_d(R(d,k)) - c^{*}k' \quad (7)$$

In the above formulation $E_d[R(d,k)]$ is the expected value of the operative revenue where expectation is taken over demand distributions and c^*k' represents the total investment costs. The firm's objective is to maximize E_d. Numerical examples exploiting the presented above model for the firm producing two products over a planning horizon during which product demands possess uncertainties are presented in (Ceryan et al., 2009).

Economics of system configurations

The next aspect of economical manufacturing system design is to calculate individual operations times needed to produce the part, where the total production time t is given. Producing a part may be, for example, machining a part by a system composed of machining centers and lathes, or assembling a part by automation or by workers. Machining a part requires calculations of the machine optimal cutting speeds which will affects the total machining time per part, and will eventually affect the number of machines needed in the system. If system capacity (based on the forecast demand) and the total time needed to produce a part are given, it is possible to calculate the minimum number of machines or stations needed in the system.

If the daily demand is D (parts/day), and the total production time per part is t (minute/part), the minimum number of machines M needed in the system is calculated by the equation:

$$M = \frac{Q * t}{A * R}, \quad (8)$$

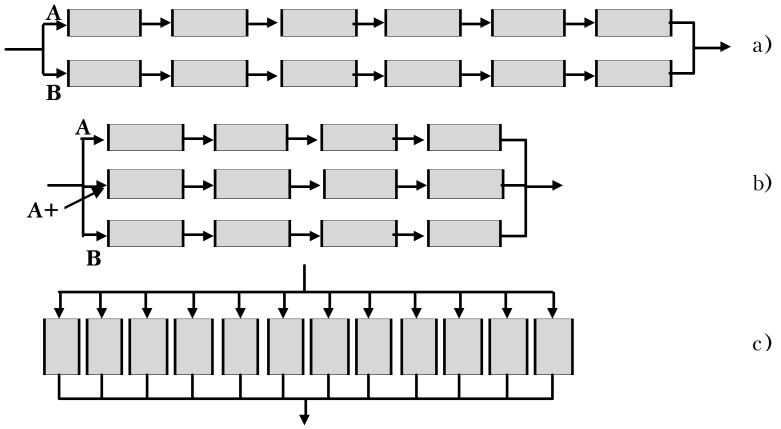
where: A – machine availability (minutes a day),

R – machine reliability.

When the number of machines is calculated, the next step is to decide upon the right configuration of a system that is composed of M machines. There may be several ways to configure a multistage manufacturing system with a given number of machines. Figure 2 shows 3 example of configuration, each with 12 machines and each produces two parts A and B. There are configurations that require a large investment in tooling (Figure 2c); in others a complex material handling system increases cost. Note that in the configuration on Figure 2a, each machine performs about one sixth of the operations needed to complete a part, and therefore the total number of tools in this system is smaller than in the other 2 configurations.

There are also cooperation considerations in selecting a configuration. If demand for part A increases by 25% and the same day the demand for Part B decreases by 25%, the configuration in Figure 2c can supply the new demand (9 machines of A and 3 of B). Satisfying the new demand with the other two systems will not be that simple and will require tool change during the day, thus reducing the daily throughput. Therefore, the configuration on Figure 2c has the best operational responsiveness of these 3 systems. This system, however requires more tools and machines with larger tool magazines, and therefore its capital investment costs are higher.

Let us compare the number of cutting tools needed to place in tool magazines of each system configuration presented on Figure 2. Assume that 20 different cutting tools are needed to produce part A, and additional 30 tools are needed for part B. In configuration (a) the total number of cutting tools in the system is 50. In the system configuration (c) if 6 machines produce part A and 6 produce part B, the total number of tools for 12 machines is 300. Accordingly, in configuration (B), the number of needed tools is 100.



Source: Developed by the author.

Figure 2. **3 examples of system configurations, all with 12 machines**

Let us also consider the impact of a single machine failures that continues more than a few hours (for example). In systems (a) and (b) below, the machining sequence is interrupted and the whole line loses productivity. If such an event causes the system, or a significant portion of it, to shut down the system is not adequately responsive.

The bottom row of Table 3 shows the percentage of throughput lost when such an event happens. Note in the configuration (a) 50% is a loss of the total production; similarly in configuration (b) 33,3% is a loss of the total production, why in the (c) configuration the loss is only 8,3%.

Table 3. **The numbers of cutting tools needed in the systems and loss throughput of machine connected to presented configurations**

	Conf. (a)	Conf. (b)	Conf. (c)
Numbers of needed cutting tools	50	100	300
Loss of throughput if one machine is down, %	50	33,3	8,3

Source: Authors.

Therefore, the choice of the best configuration is an optimal task taking into account the cost of cutting tools and machines reliability. Moreover, selecting configuration, two measures of responsiveness – system convertibility and scalability should be considered as well. However, these problems are not the subject of this paper.

Conclusions and further studies prospects

Manufacturing systems design must provide effective solutions to cope with the demand during the whole system life cycle. Therefore, this is a critical task because it entails the consideration of different criteria related to economy, finance, technology, management, customer satisfaction and human resources involvement. Moreover, the impact of external uncertainty (e.g., demand volumes and technological characteristics of products) and internal uncertainty (e.g., resource availability) should be taken into account during the design phase. As a consequence, the manufacturing system design problem must be concerned not only from the technological and organizational but also economical viewpoint.

Investment decisions for manufacturing systems are primarily based on 3 characteristics: cost of purchase and operation, cycle time in connection with maximum capacity and achievable work piece quality. However, such considerations neglect another important criterion: the flexibility that allows a manufacturing system adaptation to future production requirements and structures. The major barrier in integrating flexibility into the decision-making process is the difficulty to measure and compare it due to upcoming production scenarios that are not ultimately definable. Therefore, this paper focuses on 3 main economic tasks: life cycle economics in system selection, capacity planning strategies and systems configurations. Future research will be provided in the area of optimization in the above presented problems.

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